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(54) **GRAYSCALE LITHOGRAPHY
MANUFACTURE OF A WAVEGUIDE
DISPLAY**

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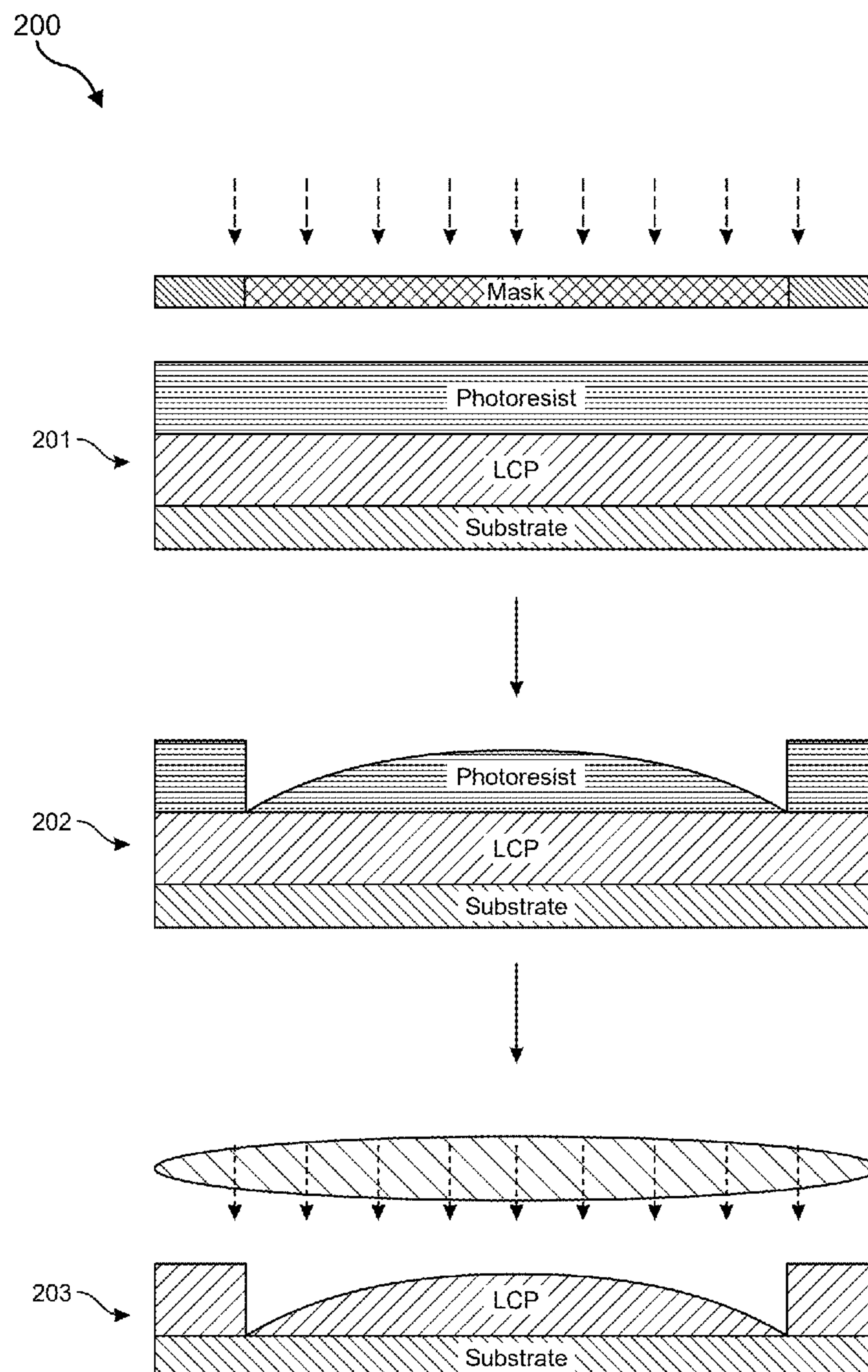
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(57) **ABSTRACT**

An optical grating includes a layer of a liquid crystal polymer, the layer having an internal grating pattern defined by locally polymerized liquid crystal molecules, where a cross-sectional shape of the layer varies across the internal grating pattern.



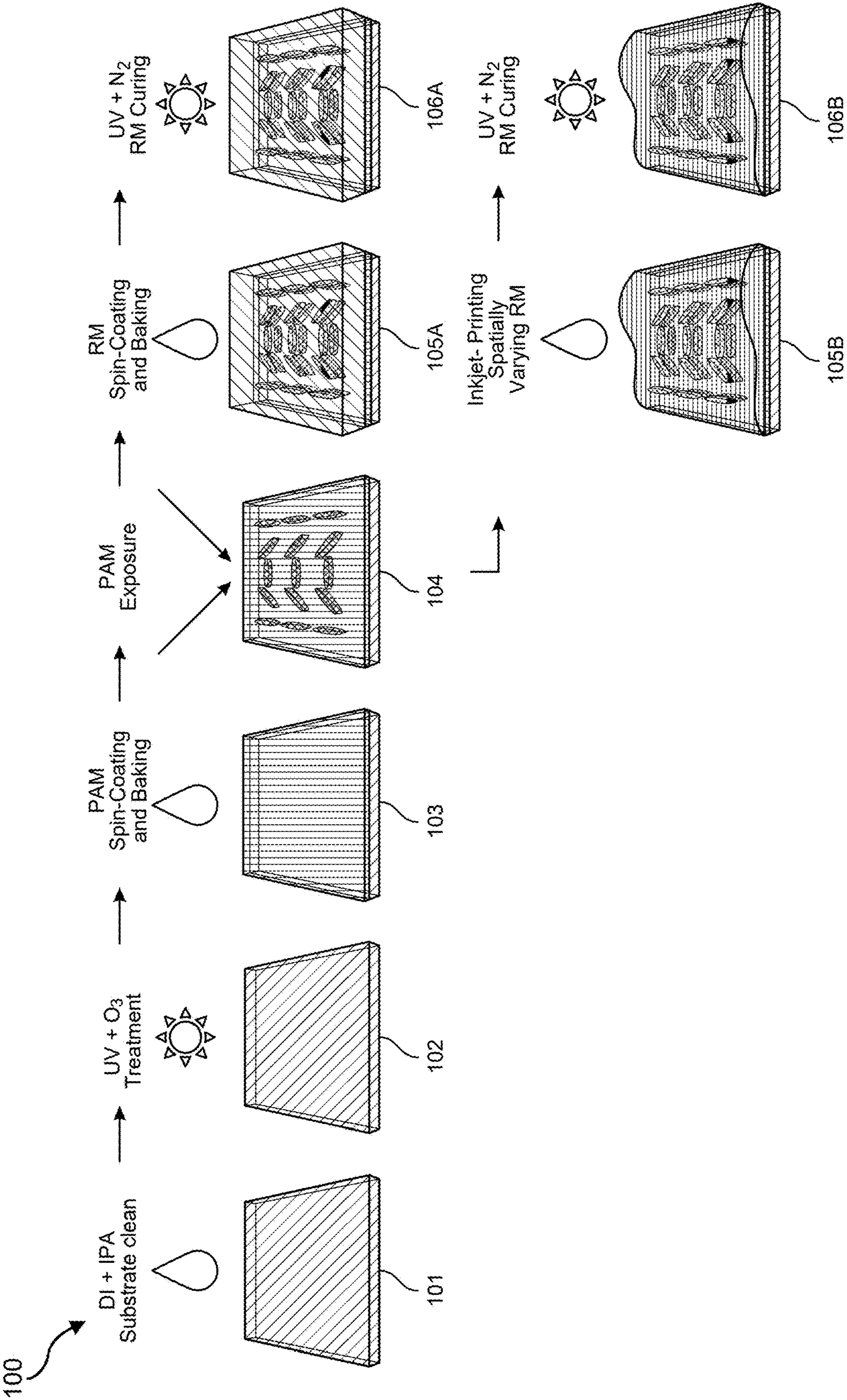


FIG. 1

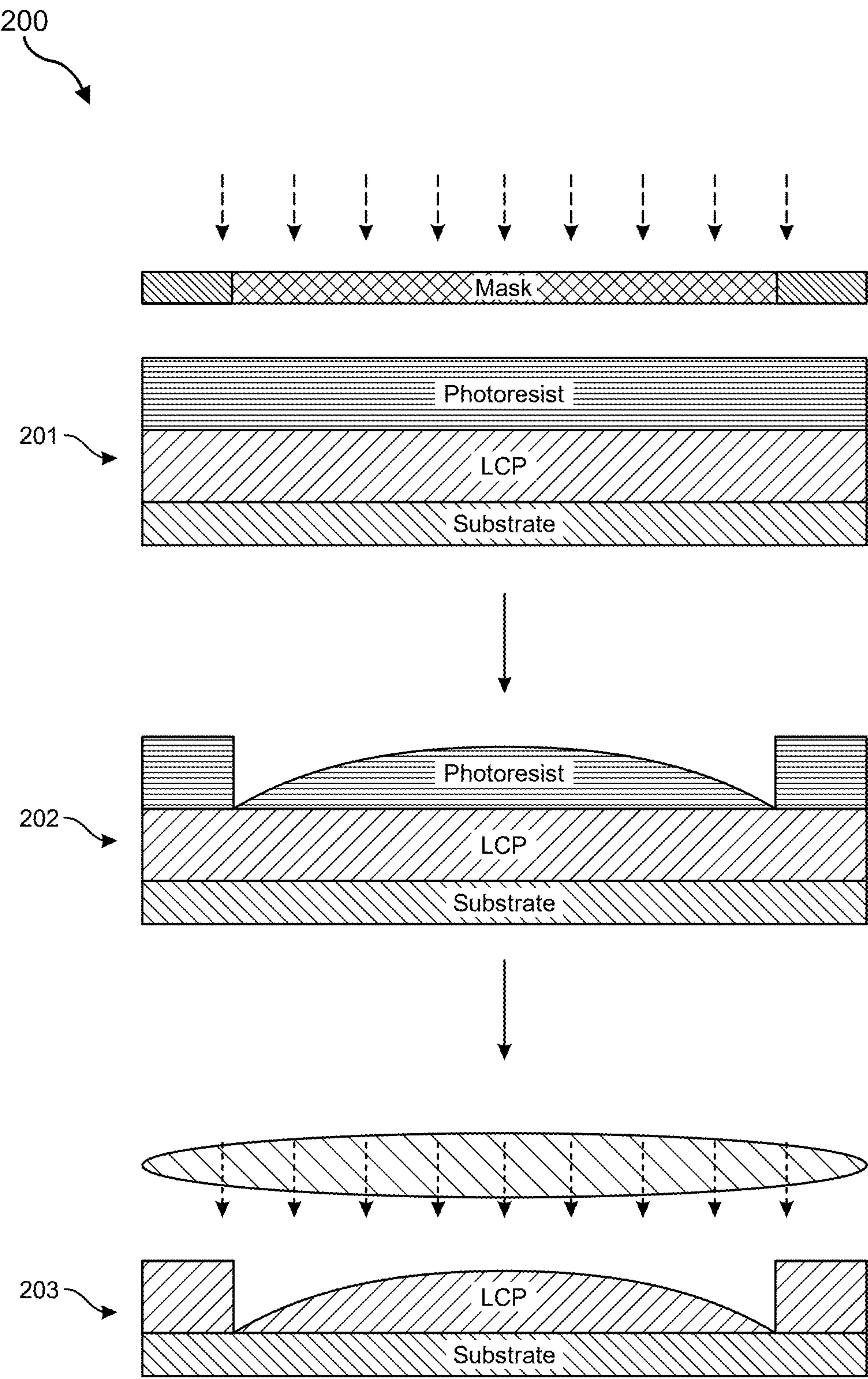


FIG. 2

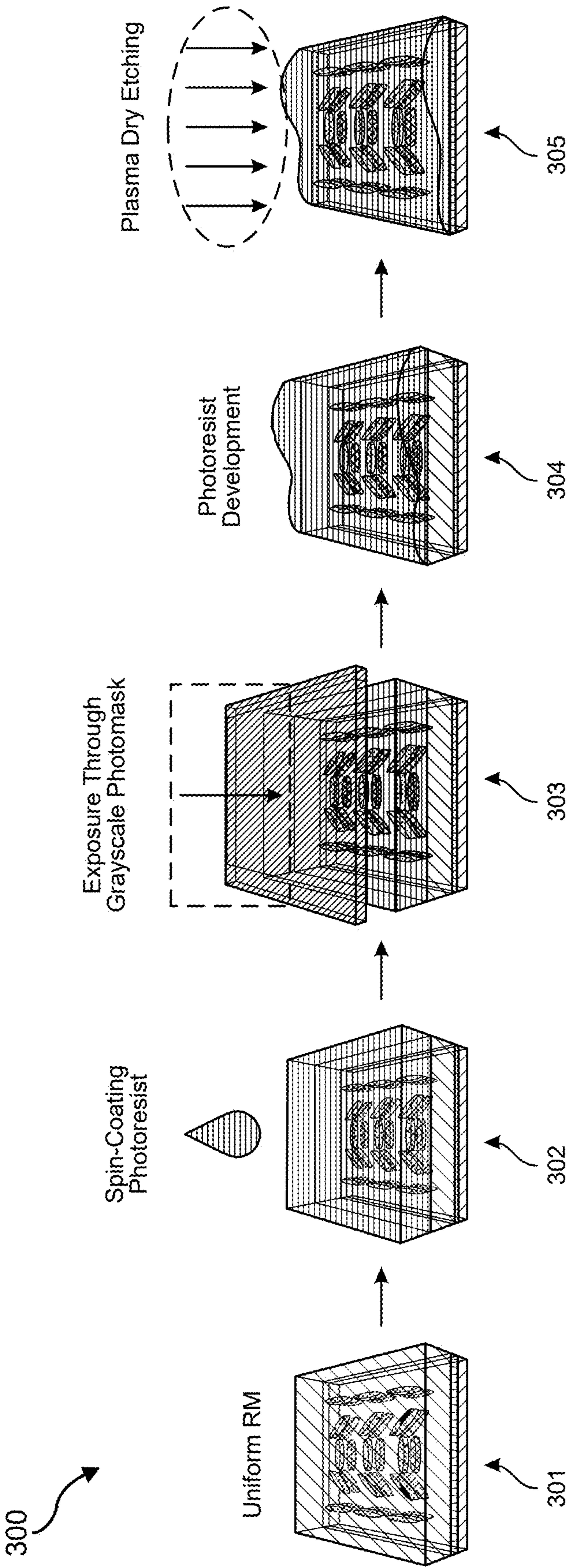


FIG. 3

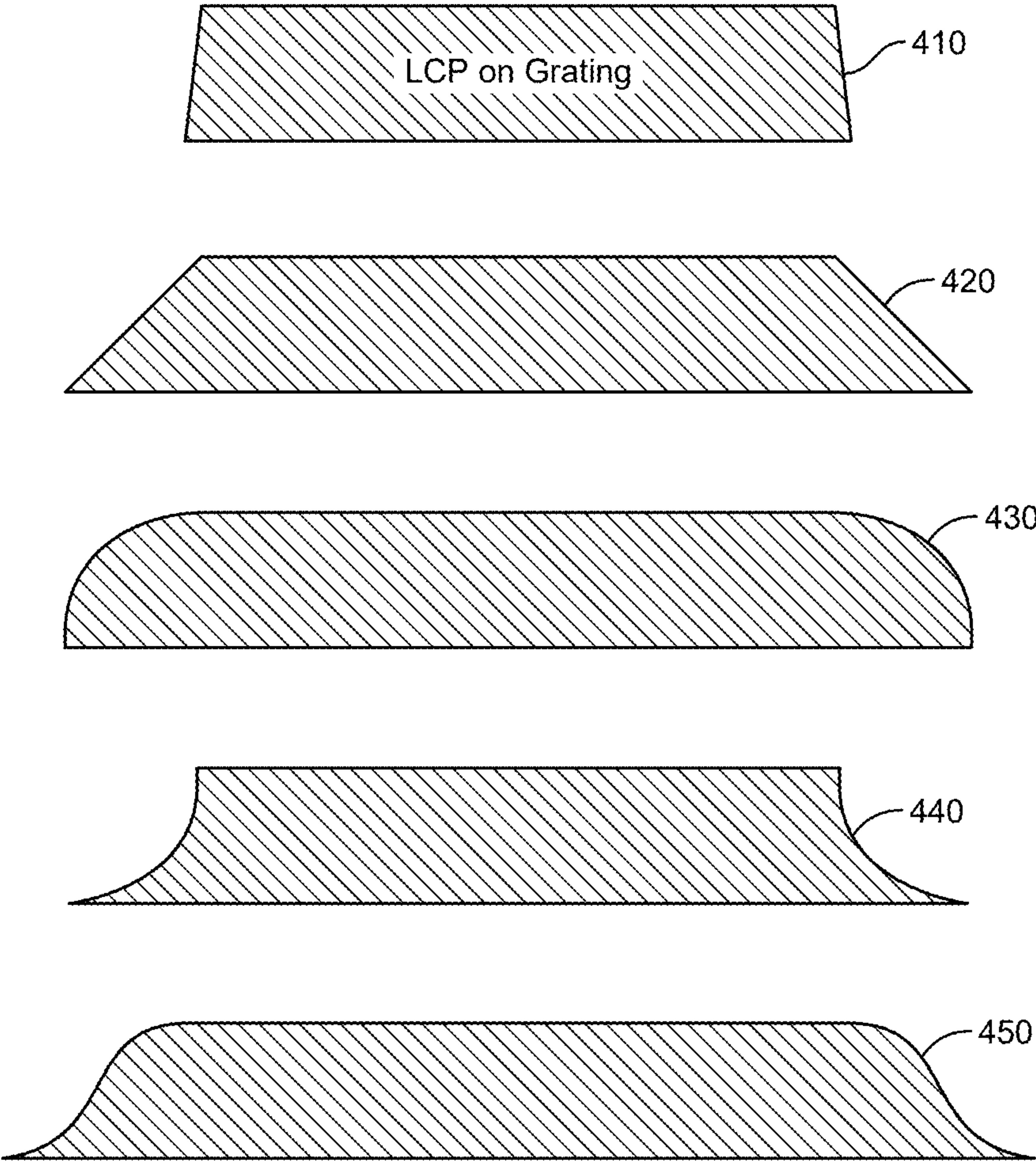


FIG. 4

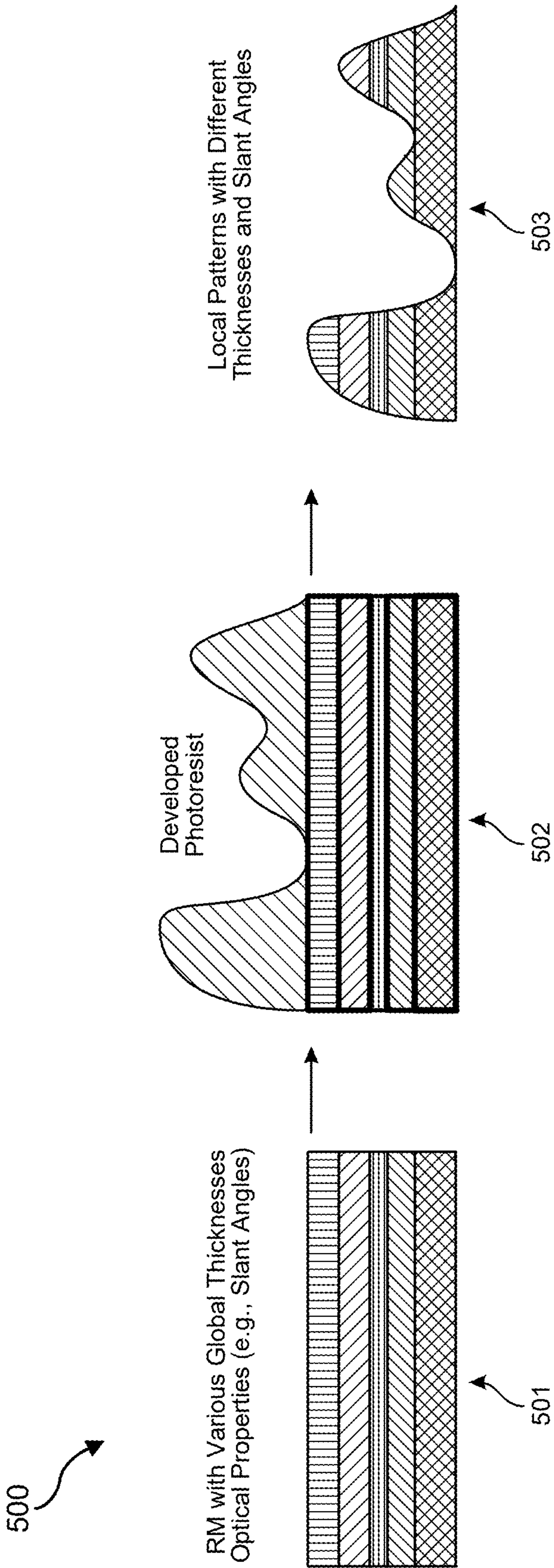


FIG. 5

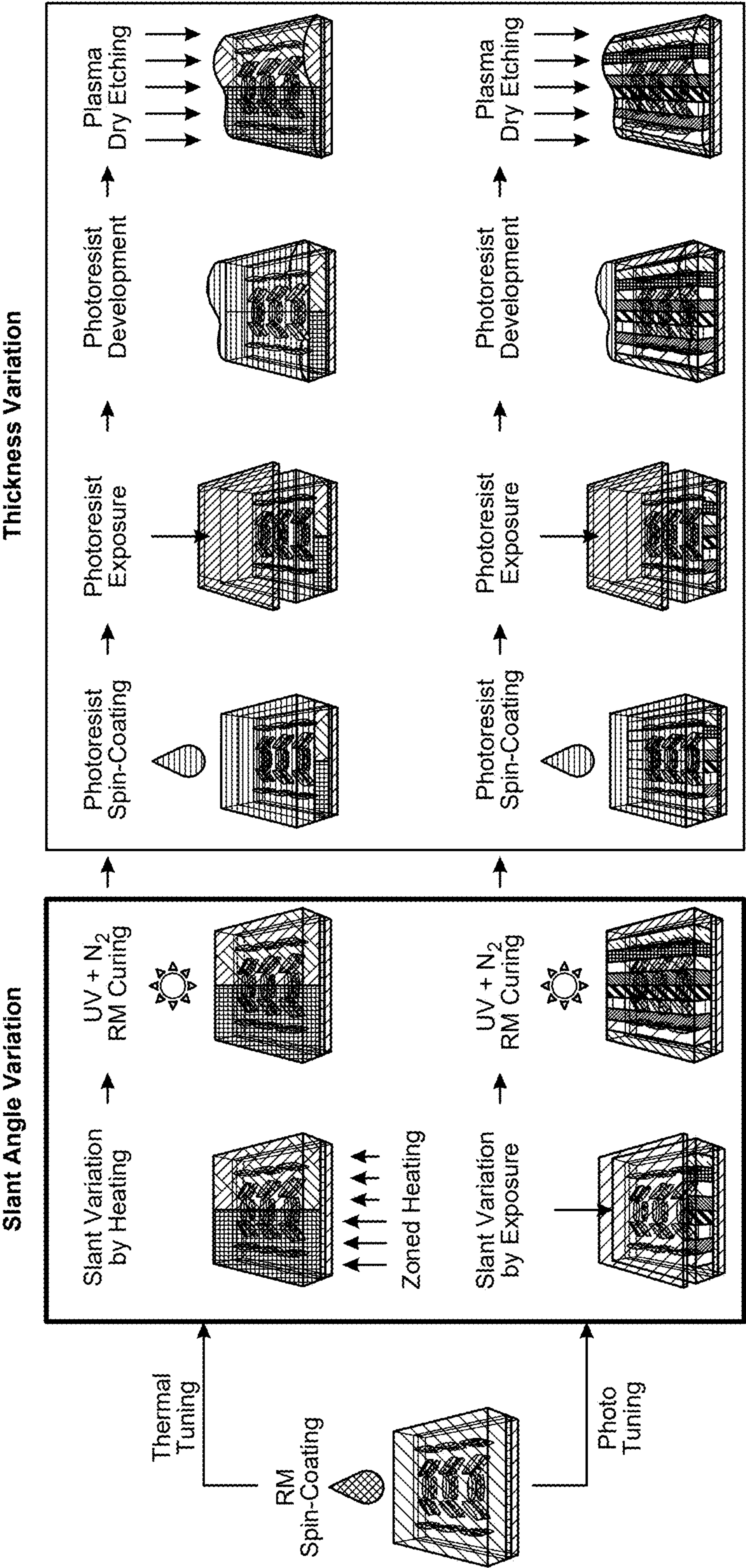


FIG. 6

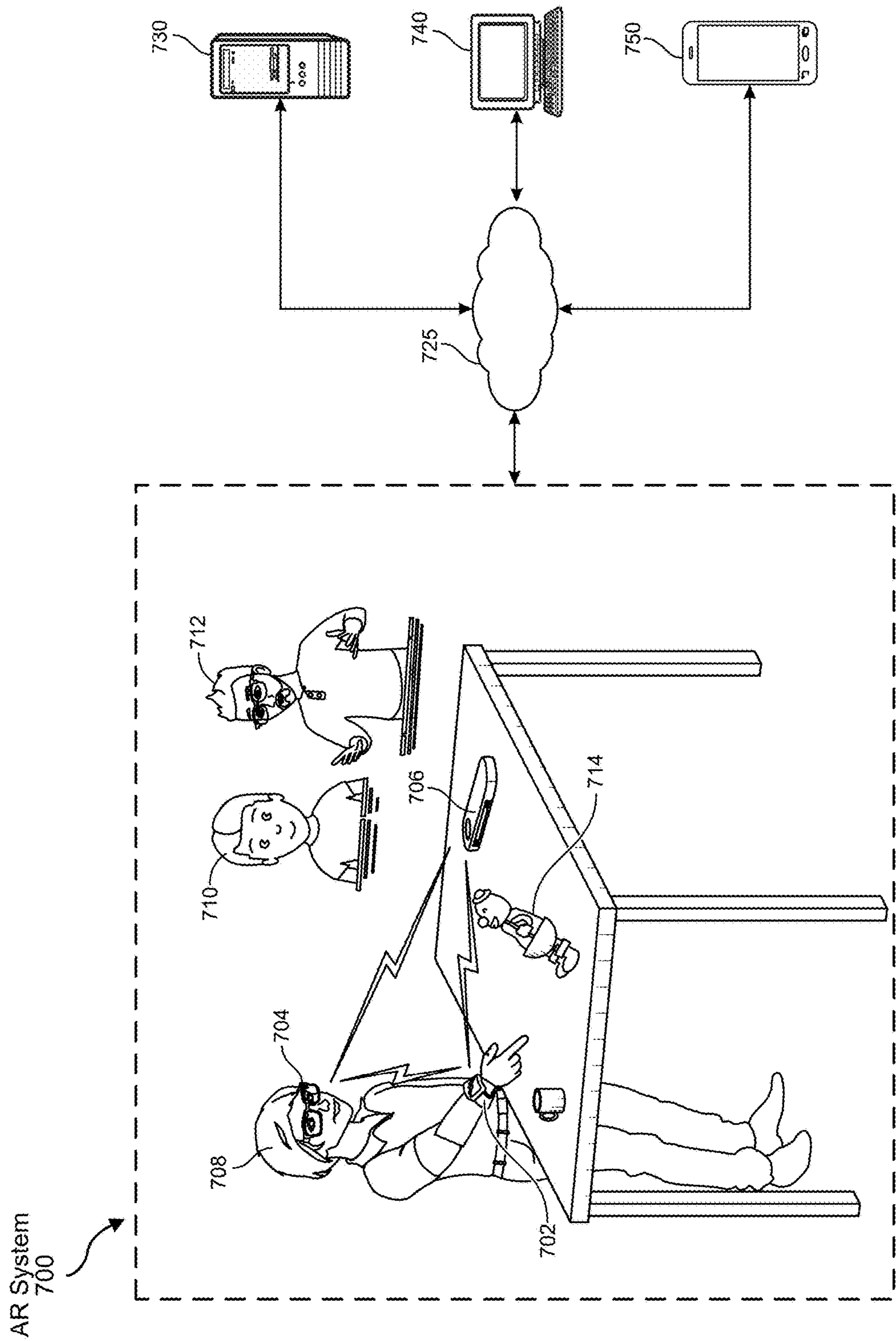


FIG. 7

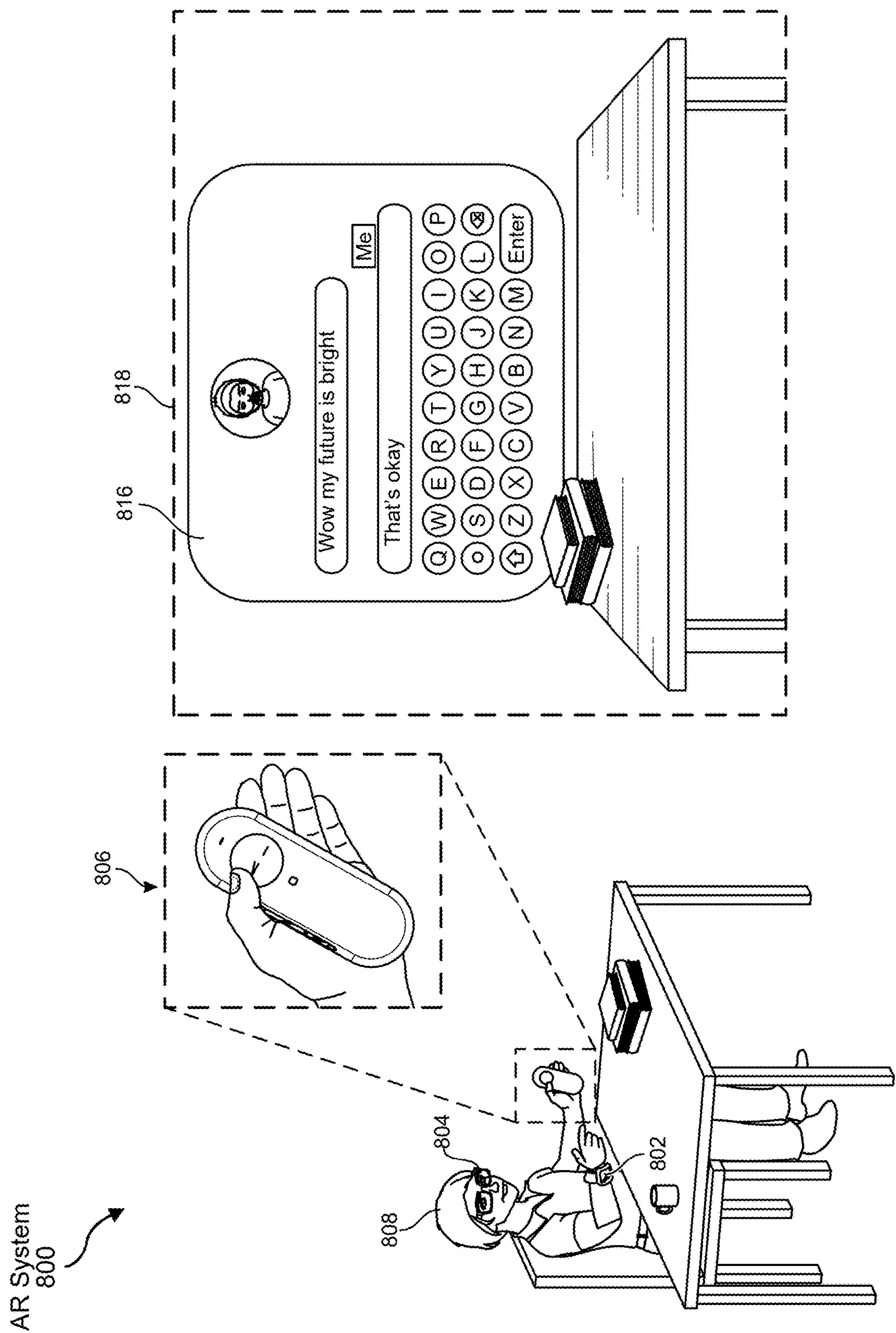


FIG. 8

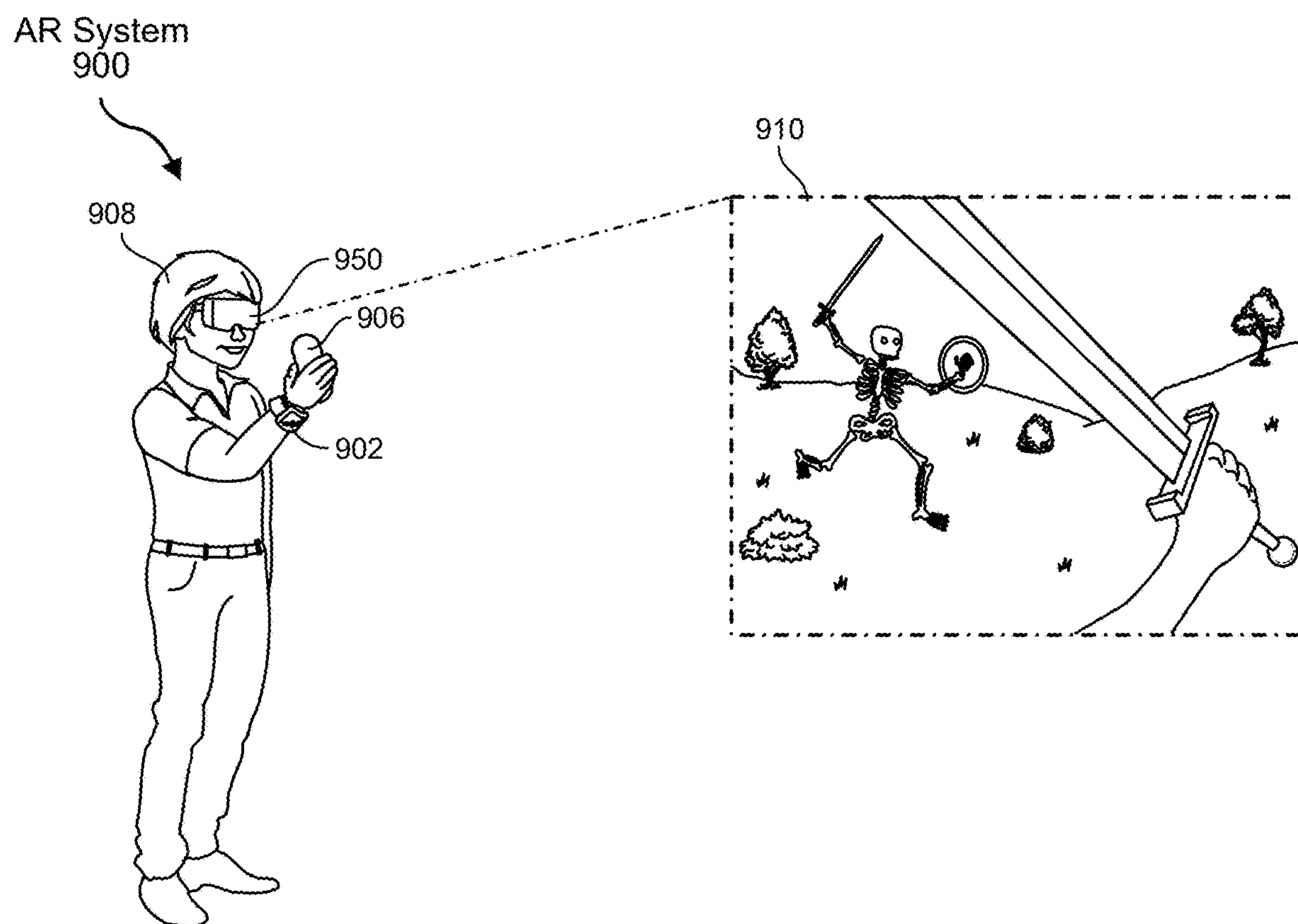


FIG. 9A

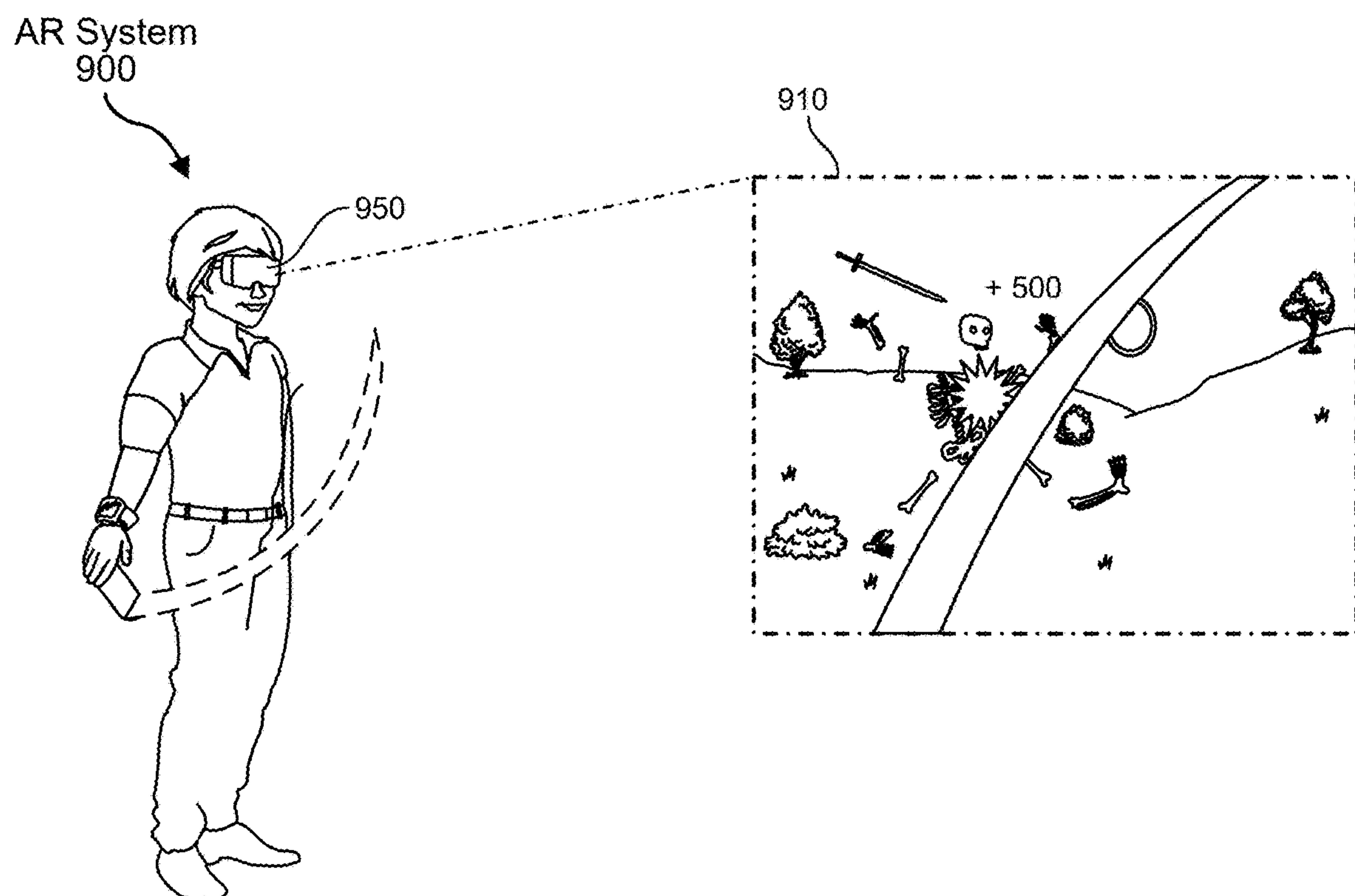


FIG. 9B

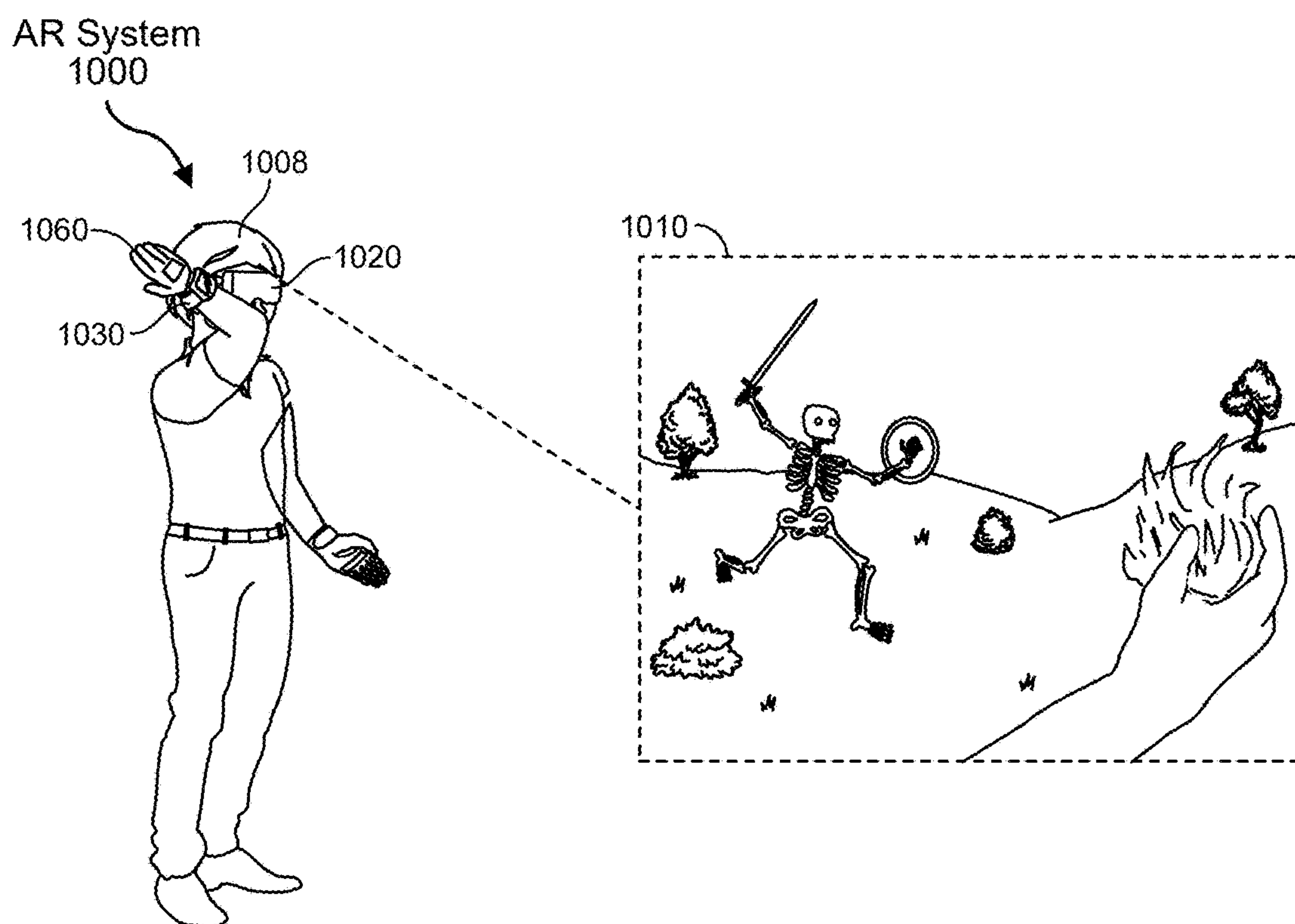


FIG. 10A

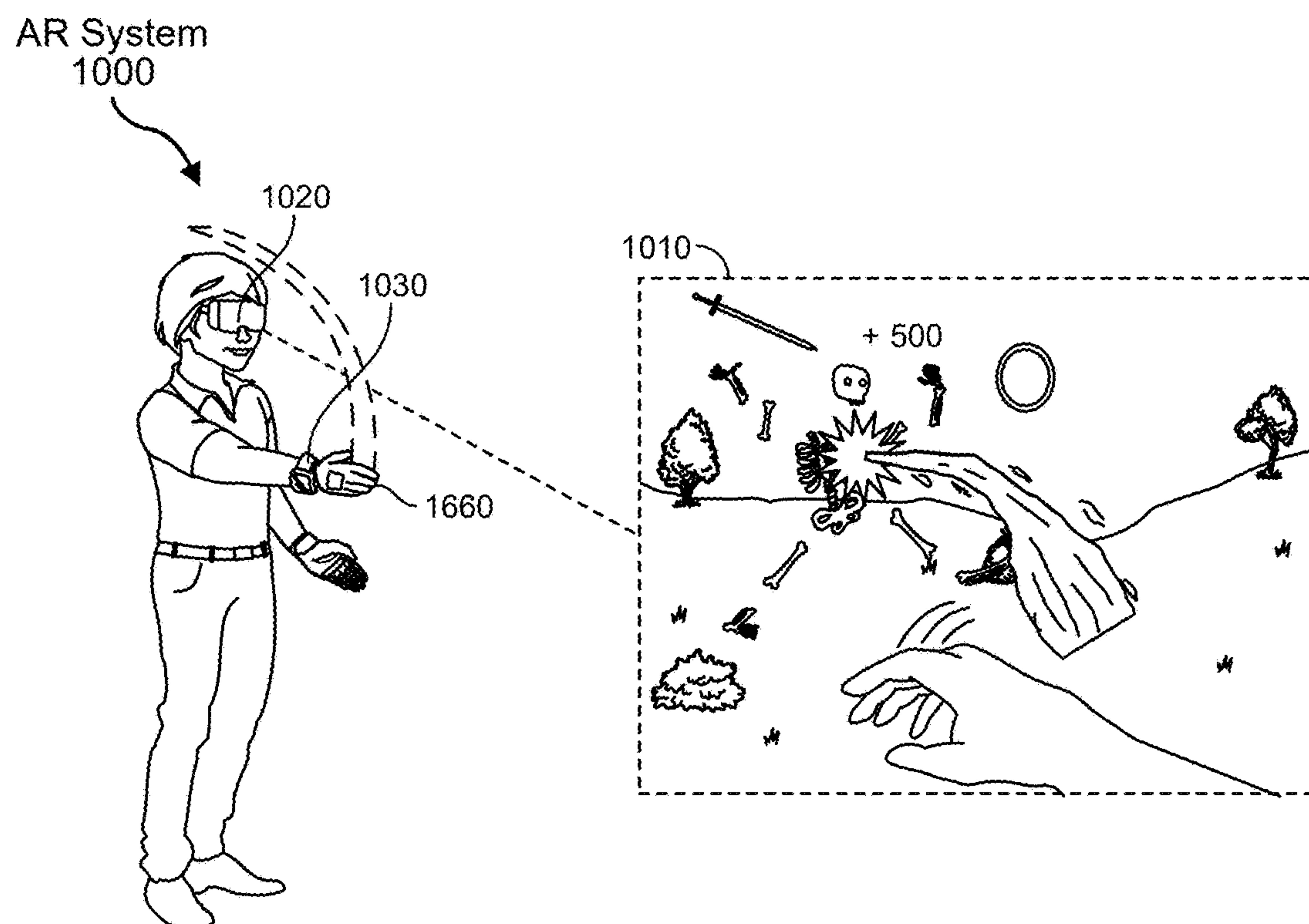


FIG. 10B

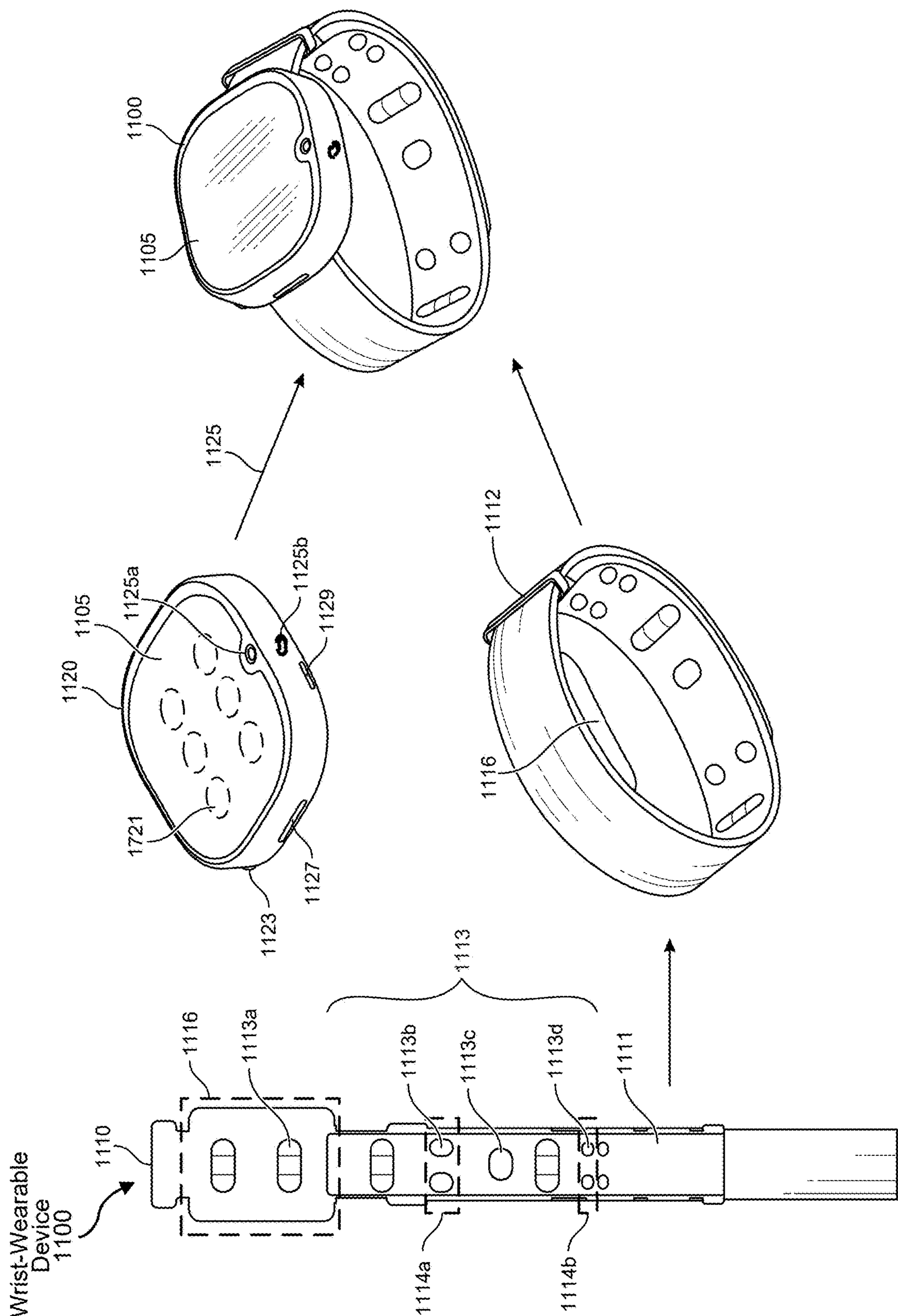


FIG. 11

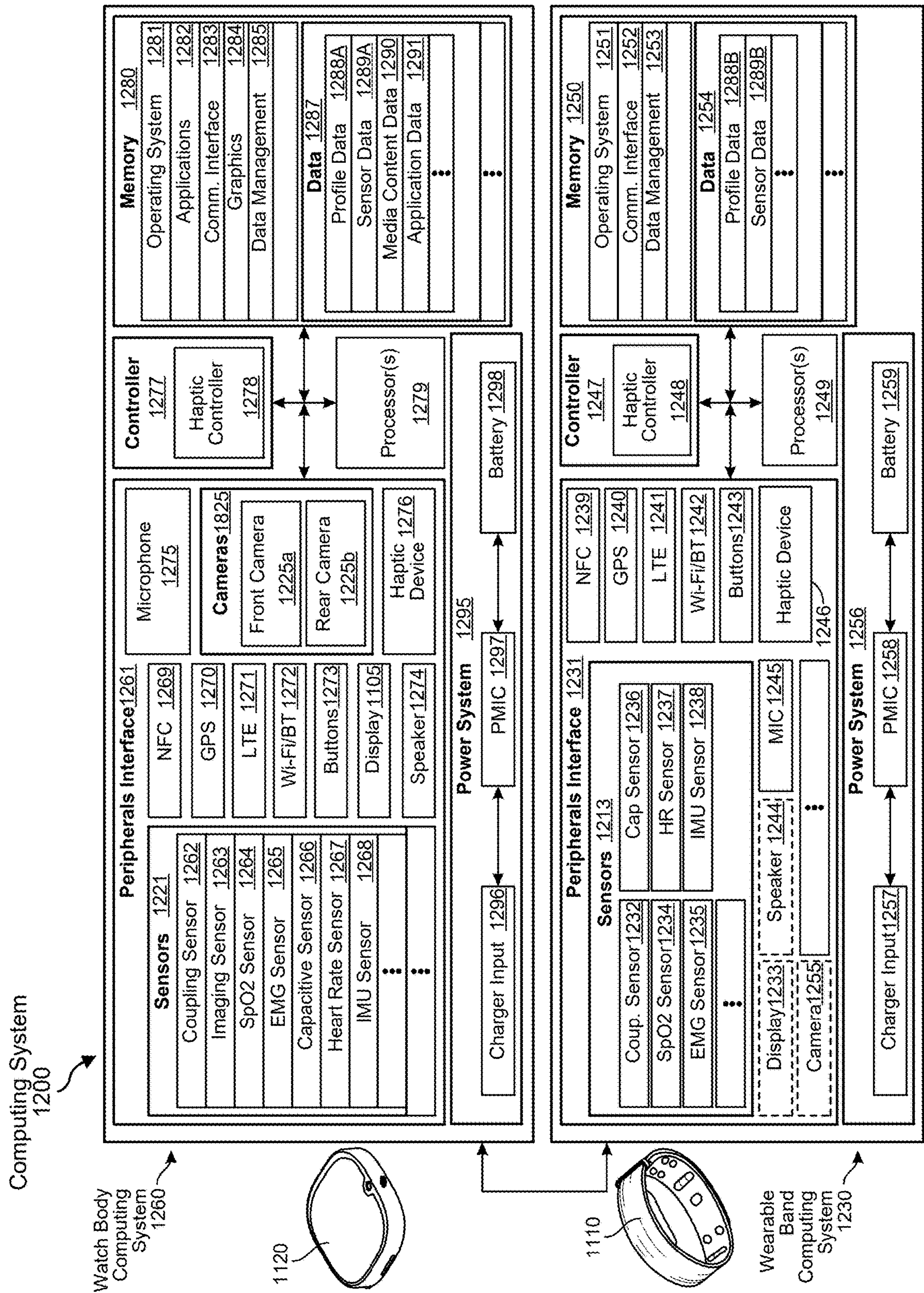


FIG. 12

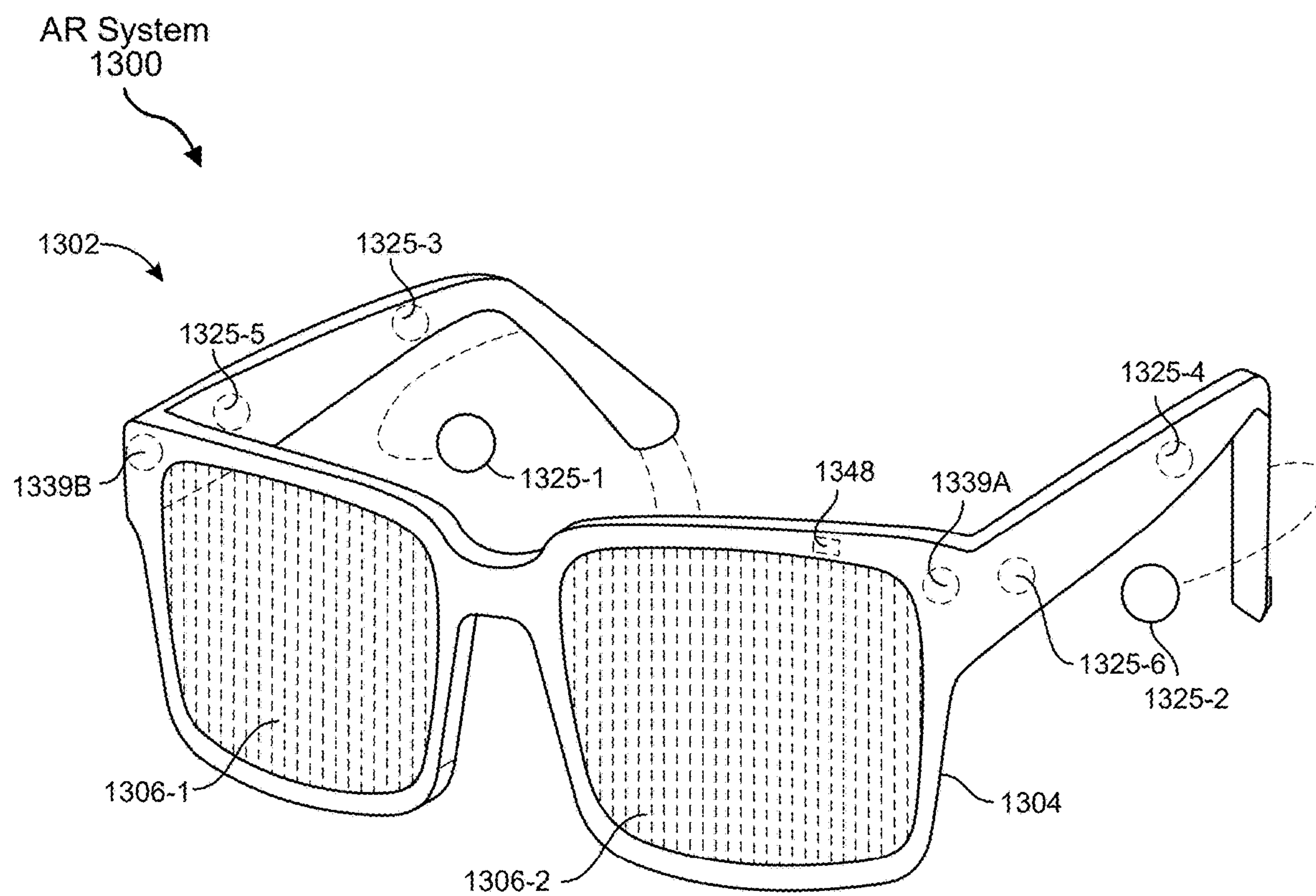


FIG. 13

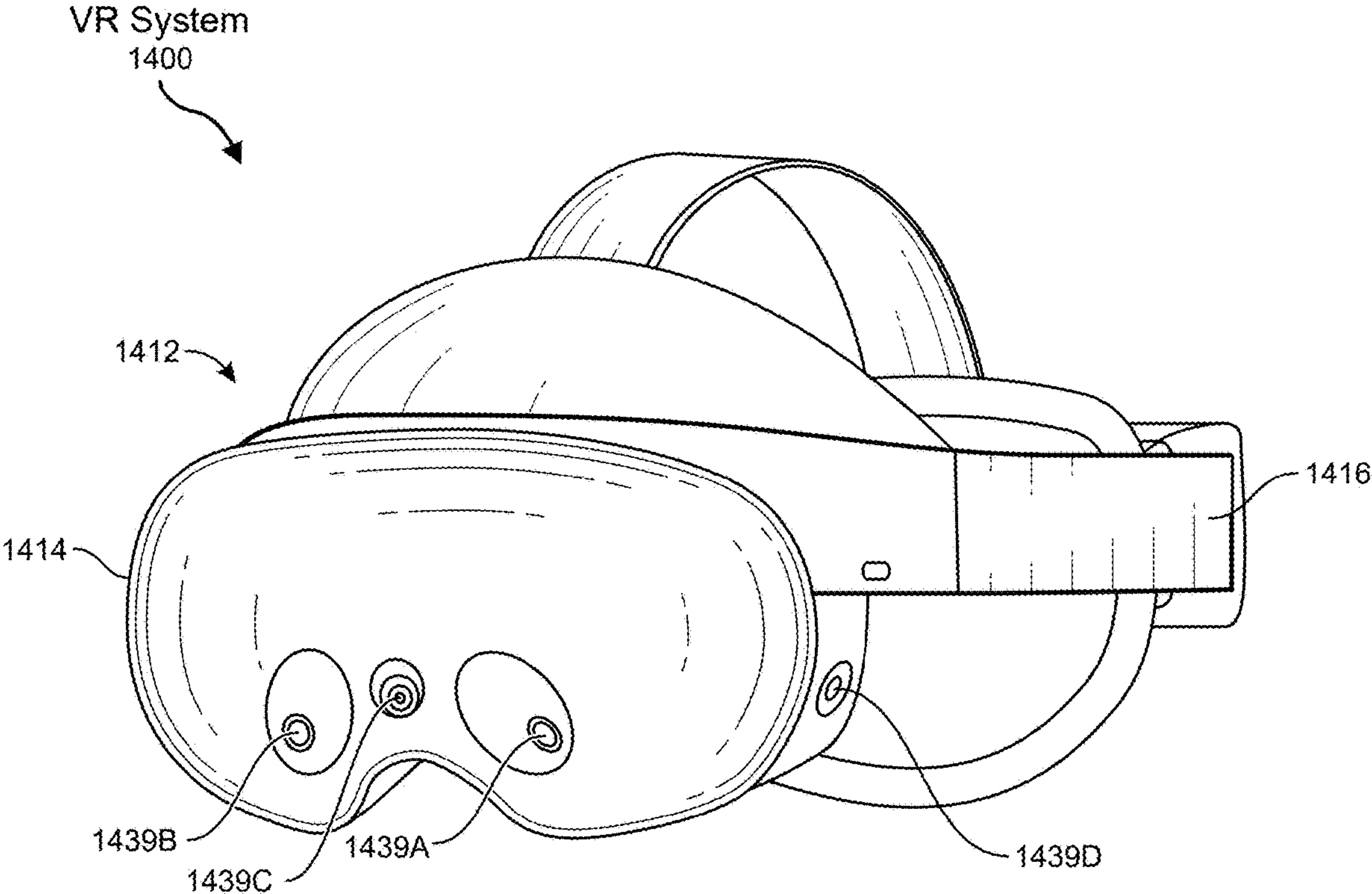


FIG. 14A

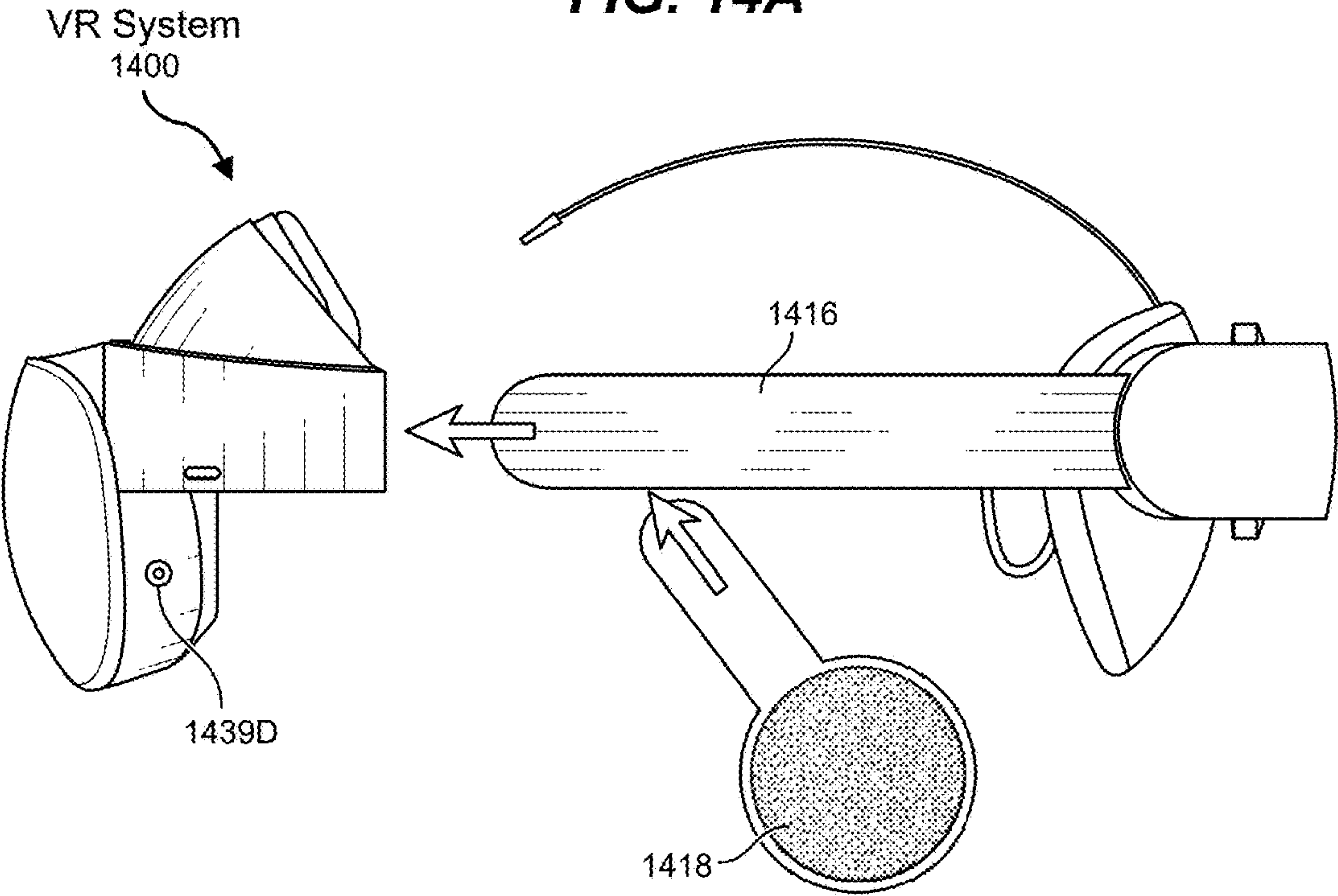


FIG. 14B

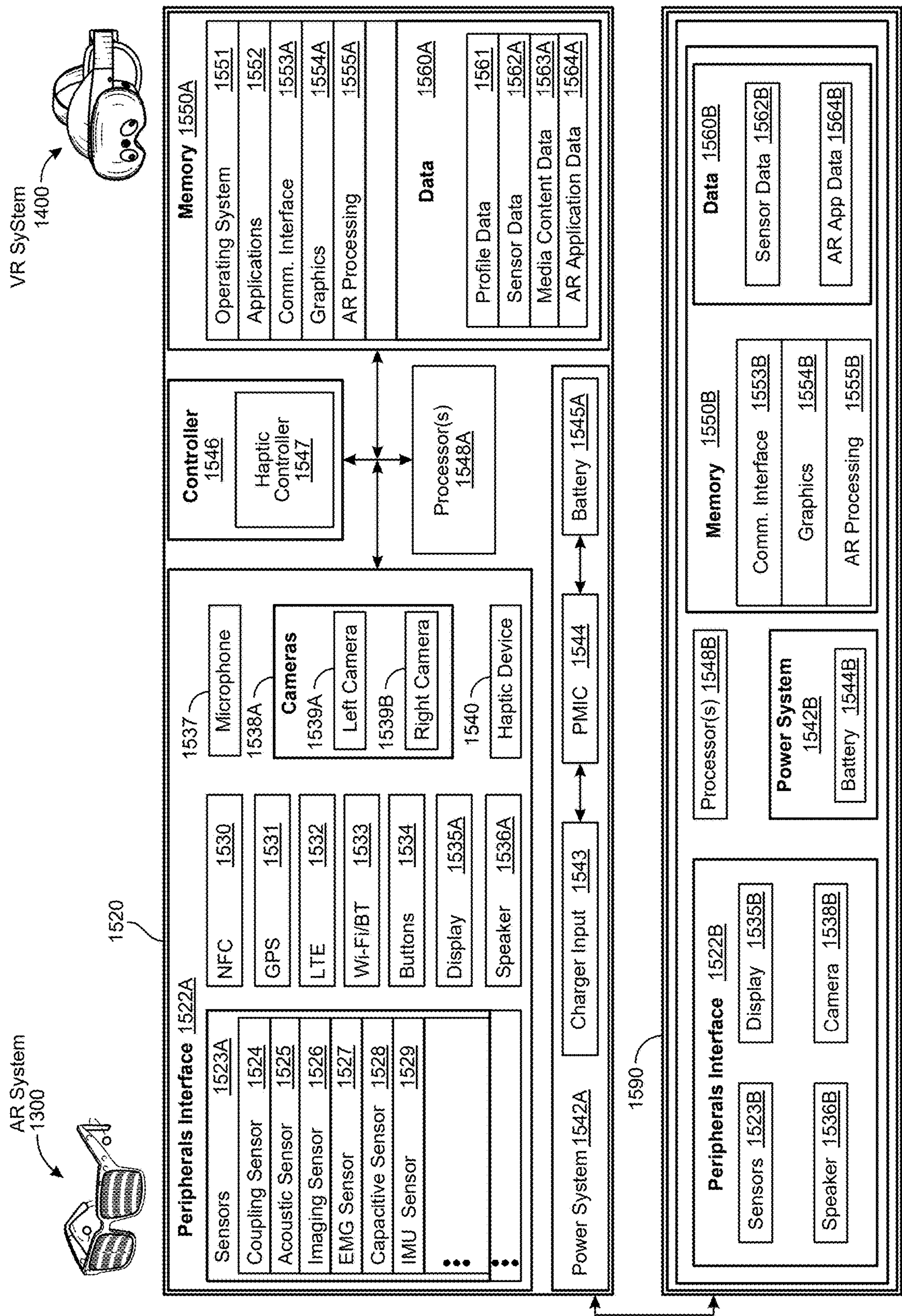


FIG. 15

GRAYSCALE LITHOGRAPHY MANUFACTURE OF A WAVEGUIDE DISPLAY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority under 35 U.S.C. § 119(e) of U.S. Provisional Application No. 63/612,194, filed Dec. 19, 2023, the contents of which are incorporated herein by reference in their entirety.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the present disclosure.

[0003] FIG. 1 illustrates aspects of a process flow for the manufacture of a waveguide display utilizing a uniform or spatially-varying reactive mesogen according to some embodiments.

[0004] FIG. 2 depicts principles of subtractive fabrication using grayscale lithography and dry etching according to certain embodiments.

[0005] FIG. 3 illustrates aspects of a process flow for the manufacture of a single layer waveguide display including a liquid crystal polymer according to some embodiments.

[0006] FIG. 4 shows the impact of grayscale lithography on edge profile control for various etched structures according to some embodiments.

[0007] FIG. 5 illustrates aspects of a process flow for the manufacture of a multi-layer waveguide display including a liquid crystal polymer according to some embodiments.

[0008] FIG. 6 depicts the generation of a waveguide display having both in-plane and out-of-plane feature variability according to certain embodiments.

[0009] FIG. 7 is an illustration of an example artificial-reality system according to some embodiments of this disclosure.

[0010] FIG. 8 is an illustration of an example artificial-reality system with a handheld device according to some embodiments of this disclosure.

[0011] FIG. 9A is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0012] FIG. 9B is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0013] FIG. 10A is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0014] FIG. 10B is an illustration of example user interactions within an artificial-reality system according to some embodiments of this disclosure.

[0015] FIG. 11 is an illustration of an example wrist-wearable device of an artificial-reality system according to some embodiments of this disclosure.

[0016] FIG. 12 is an illustration of an example wearable artificial-reality system according to some embodiments of this disclosure.

[0017] FIG. 13 is an illustration of an example augmented-reality system according to some embodiments of this disclosure.

[0018] FIG. 14A is an illustration of an example virtual-reality system according to some embodiments of this disclosure.

[0019] FIG. 14B is an illustration of another perspective of the virtual-reality system shown in FIG. 14A.

[0020] FIG. 15 is a block diagram showing system components of example artificial-and virtual-reality systems.

[0021] Throughout the drawings, identical reference characters and descriptions indicate similar, but not necessarily identical, elements. While the exemplary embodiments described herein are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. However, the exemplary embodiments described herein are not intended to be limited to the particular forms disclosed. Rather, the present disclosure covers all modifications, equivalents, and alternatives falling within the scope of the appended claims.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0022] Virtual reality (VR) and augmented reality (AR) eyewear devices and headsets enable users to experience events, such as interactions with people in a computer-generated simulation of a three-dimensional world or viewing data superimposed on a real-world view. Superimposing information onto a field of view may be achieved through an optical head-mounted display (OHMD) or by using embedded wireless glasses with a transparent heads-up display (HUD) or augmented reality overlay. VR/AR eyewear devices and headsets may be used for a variety of purposes. Governments may use such devices for military training, medical professionals may use such devices to simulate surgery, and engineers may use such devices as design visualization aids.

[0023] Virtual reality and augmented reality devices and headsets typically include an optical system having a micro-display and imaging optics. Display light may be generated and projected to user through a display system, such as where the light is in-coupled into a waveguide, transported therethrough by total internal reflection (TIR), replicated to form an expanded field of view, and out-coupled when reaching the position of a viewer's eye.

[0024] A waveguide display system, for example, may include a micro-display module and waveguide optics for directing a display image to a user. The waveguide optics may include input-coupling and output-coupling elements such as surface relief gratings that are configured to couple light into and out of the waveguide. A vertical grating coupler, for instance, may be configured to change an out-of-plane wave-vector direction of light to an in-plane waveguide direction, or vice versa, and accordingly direct the passage of light through the waveguide display.

[0025] In exemplary systems, waveguide optics may be advantageously configured to create illuminance uniformity and a wide field of view (FOV). The FOV relates to the angular range of an image observable by a user, whereas illuminance uniformity may include both the uniformity of image light over an expanded exit pupil (exit pupil uniformity) and the uniformity of image light over the FOV (angular uniformity). As will be appreciated, one or both of an input-coupling grating and an output-coupling grating may determine the angular uniformity and coupling effi-

ciency of image light, which may derive from structure of the gratings and the properties of the constituent material.

[0026] Waveguide elements may be formed using liquid crystal materials. Liquid crystal polymers (LCPs) have the properties of a liquid crystal, which for display applications may include high resolution, high brightness, and potentially low manufacturing costs. Liquid crystal polymers may be incorporated into various elements of a waveguide display system, including diffractive gratings, and may support the fabrication of thin (planar) and cost-effective optical components such as polarization volume holograms (PVHs).

[0027] Reactive mesogens (RMs) are a class of liquid crystal material with the characteristic property of possessing polymerizable groups. The presence of these groups allows for the polymerization of the material in its liquid crystal phase to produce a solid, optically anisotropic polymer. Due to the nature of pupil replication and intrinsic absorption by liquid crystal media, however, it remains a challenge to achieve color uniformity and overall high operational efficiency in a uniform and homogeneous LCP diffractive waveguide.

[0028] Notwithstanding recent developments, it would be advantageous to provide methods for the manufacture of efficient LCP diffractive waveguides that exhibit good color uniformity and superior image quality.

[0029] In accordance with certain embodiments, grayscale lithography and plasma dry etching may be utilized in the design and fabrication of liquid crystal polymer (LCP)-based waveguides. The disclosed processing techniques may be used to introduce freeform thickness variation in a liquid crystal polymer layer, provide improved optical properties, and enable active edge profile control at grating boundaries, which may beneficially improve pupil efficiency, color uniformity, contrast, and clarity in an associated waveguide display.

[0030] In particular embodiments, concurrent control of thickness variation and edge profile can be realized in a single lithography-etch step, decreasing haze, improving image contrast, and greatly simplifying the fabrication process, which may decrease unit marginal costs in mass production. In conjunction with the foregoing, multi-layer LCPs with vertically varying optical properties can be fabricated by spin-coating multiple layers with distinctive formulations. Furthermore, in-plane optical property variation (e.g., slant angle variation) can be introduced into LCPs by external tuning stimulation, prior to utilizing one or more of the above features for additional thickness variation and edge control.

[0031] With thickness variation and multi-layer fabrication provided with a single grayscale lithography-etching step, it may be possible to utilize more degrees of freedom in design and create waveguides with higher efficiency, brightness, and color uniformity. With active edge profile control achieved by grayscale lithography and etching, light scattering from the physical grating boundaries can be decreased, which may effectively improve the image contrast in the fabricated waveguide display. Various functional impacts can be combined into a concurrent design and implemented within the same fabrication step, greatly improving the economics of manufacture.

[0032] An example method includes forming a layer of photo-alignment material over a substrate, selectively irradiating the layer of photo-alignment material with polarized light to form a grating pattern in the layer of photo-

alignment material, forming a layer of reactive mesogen over the patterned layer of photo-alignment material, transferring the grating patterning into the layer of reactive mesogen, forming a layer of photoresist over the layer of reactive mesogen, directing exposing light through a grayscale photomask having transparent areas corresponding to a gray-tone pattern to produce masked light, directing the masked light onto the layer of photoresist, developing the photoresist to produce a three dimensional structure in the layer of photoresist, and plasma etching the layer of photoresist and the layer of reactive mesogen to form the three dimensional structure in the layer of reactive mesogen.

[0033] The following will provide, with reference to FIGS. 1-15, detailed descriptions of display architectures formed using grayscale photolithography and dry etching processes. The discussion associated with FIGS. 1-6 includes a description of grayscale lithography and etching processes and example optical display architectures formed using such processes. The discussion associated with FIGS. 7-15 relates to exemplary virtual reality and augmented reality devices that may include one or LCP-based waveguides as disclosed herein.

[0034] Referring to FIG. 1, shown are substantially parallel processing routes for the manufacture of a polarization volume hologram (PVH) with a layer of reactive mesogen (RM) having uniform thickness or spatially-varying thickness. In the illustrated embodiments, a spin coating technique may be used to form a reactive mesogen layer having a substantially constant thickness while an inkjet printing process may be used to form a variable thickness RM layer.

[0035] The process flow 100 of FIG. 1 may include preparing a suitable substrate, which may include pre-cleaning (step 101) and surface treating (step 102) the substrate. Pre-cleaning may include rinsing a surface of the substrate with de-ionized water and/or alcohol (e.g., isopropyl alcohol), and surface treating may include exposure of the substrate to ultraviolet light and/or ozone. In certain embodiments, the substrate is a glass substrate.

[0036] In step 103, a layer of photoalignment material (PAM) may be deposited over the substrate. The photoalignment material layer may be formed by spin-coating and, following thermal treatment, exposed to patterned radiation to introduce a desired internal structure of the photoalignment material (step 104).

[0037] Referring initially to step 105A, a uniform layer of reactive mesogen may be formed over the patterned photoalignment material layer. The uniform reactive mesogen layer may be formed by spin-coating followed by thermal treatment and, referring to step 106A, exposed to radiation (e.g., UV light) and cured whereby the patterned structure in the photoalignment material layer is transferred into the reactive mesogen layer.

[0038] Alternatively, and with reference to step 105B, a non-uniform layer of reactive mesogen may be formed over the patterned photoalignment material layer. The non-uniform (i.e., spatially varying) reactive mesogen layer may be formed by 3D-printing followed by thermal treatment and, referring to step 106B, exposed to radiation (e.g., UV light) and cured whereby the patterned structure in the photoalignment material layer is transferred into the reactive mesogen layer.

[0039] Principles of grayscale lithography and etching are illustrated schematically in FIG. 2. Grayscale lithography may be configured to create a thickness variation profile in

a layer of developed photoresist by modulating the local exposure dose via a grayscale photomask. The grayscale photoresist may have a non-binary (low-contrast) response to light exposure from which a continuous thickness variation in the photoresist layer may be achieved. The 3D profile in the photoresist remaining after development may be transferred to an underlying liquid crystal polymer (LCP) layer via plasma etching. In the schematic of FIG. 2, an example process 200 may include the sequential acts of grayscale exposure (201), photoresist development (202), and plasma etching (203).

[0040] Turning to FIG. 3, shown is a process flow 300 for the formation of a grating architecture in a single LCP layer. Referring also to the process outlined in FIG. 1, a uniform layer of a reactive mesogen may be formed over the photoalignment layer following exposure of the photoalignment layer to generate a grating pattern therein (step 301). A layer of photoresist is formed over the RM layer (step 302) and the photoresist is exposed through a grayscale mask (step 303) and developed (step 304). Using the grayscale mask as a sacrificial hard mask, the thickness profile in the photoresist layer may be transferred to the underlying reactive mesogen layer using plasma etching (step 305).

[0041] Grayscale lithography and etching may enable freeform control of the edge profile at the grating boundaries. As shown in FIG. 4, a large range of edge styles and profiles can be formed, including no active control with an abrupt edge 410, a linear edge 420, a convex edge 430, a concave edge 440, or a spline edge 450. As will be appreciated, the extended edge profile and accompanying continuous features can significantly improve image contrast in a resulting waveguide.

[0042] Referring to FIG. 5, reactive mesogen layers with different thicknesses and optical properties (e.g., slant angles) may be spin-coated and arranged in a single stack, introducing a variation in properties along a thickness dimension. Utilizing a single-step grayscale lithography and etch process, wafer-level 3D structures patterned with a chosen combination of thicknesses and optical properties can be formed. Coupling thickness variation with optical property variation along the vertical axis can increase the degrees of freedom for waveguide design and fabrication. An example process 500 may include spin-coating a multi-layer RM stack (step 501), defining a desired profile using grayscale lithography (step 502), and transferring the profile into the RM stack using plasma etching (step 503).

[0043] Referring to FIG. 6, additional in-plane optical property variation (i.e., slant angle variation) can be introduced through thermal and/or photoactive stimulation prior to grayscale lithography and etching.

[0044] In accordance with various embodiments, a single grayscale lithography and etch step may be used to form a diffractive waveguide having desirable characteristics, including a single-layer with variable thickness or a multi-layer with vertically-varying optical properties. The disclosed methods may additionally provide active control of the edge profile at grating boundaries. Additional design and fabrication degrees of freedom can be introduced by adding spatially-varying optical properties in-plane prior to the grayscale lithography and etch step.

EXAMPLE EMBODIMENTS

Example 1

[0045] A method includes forming a layer of reactive mesogen having an internal grating patterning and modifying a cross-sectional shape of the layer of reactive mesogen proximate to the internal grating pattern.

Example 2

[0046] The method of Example 1, where forming the layer of reactive mesogen includes spin coating.

Example 3

[0047] The method of any of Examples 1 and 2, where the internal grating pattern includes locally polymerized liquid crystal molecules.

Example 4

[0048] The method of any of Examples 1-3, where modifying the cross-sectional shape of the layer of reactive mesogen includes plasma etching.

Example 5

[0049] The method of any of Examples 1-4, where forming the layer of reactive mesogen includes forming a first layer of reactive mesogen including a first internal grating patterning and forming a second layer of reactive mesogen including a second internal grating patterning over the first layer of reactive mesogen.

Example 6

[0050] The method of any of Examples 1-5, where modifying the shape of the layer of reactive mesogen includes forming a layer of photoresist over the layer of reactive mesogen, positioning a grayscale photomask over the layer of photoresist, the photomask having transparent areas corresponding to a gray-tone pattern, directing exposing light through the photomask and onto the layer of photoresist, developing the photoresist to produce a three dimensional structure in the layer of photoresist, and plasma etching the layer of photoresist and the layer of reactive mesogen to form the three dimensional structure in the layer of reactive mesogen.

Example 7

[0051] The method of Example 6, where the three dimensional structure in the layer of reactive mesogen includes sloped sidewalls.

Example 8

[0052] The method of any of Examples 6 and 7, where the three dimensional structure in the layer of reactive mesogen includes sidewalls having a profile selected from convex, concave, and spline.

Example 9

[0053] The method of any of Examples 6-8, where the three dimensional structure in the layer of reactive mesogen has a variable thickness.

Example 10

[0054] An optical grating includes a layer having a liquid crystal polymer, the layer including an internal grating pattern defined by locally polymerized liquid crystal molecules, where a cross-sectional shape of the layer varies across the internal grating pattern.

Example 11

[0055] The optical grating of Example 10, where the cross-sectional shape has a variable thickness.

Example 12

[0056] The optical grating of any of Examples 10 and 11, where the cross-sectional shape includes sidewalls having a profile selected from convex, concave, and spline.

Example 13

[0057] A method includes forming a layer of photo-alignment material over a substrate, selectively irradiating the layer of photo-alignment material with polarized light to form a grating pattern in the layer of photo-alignment material, forming a layer of reactive mesogen over the patterned layer of photo-alignment material, transferring the grating patterning into the layer of reactive mesogen, forming a layer of photoresist over the layer of reactive mesogen, directing exposing light through a grayscale photomask having transparent areas corresponding to a gray-tone pattern to produce masked light, directing the masked light onto the layer of photoresist, developing the photoresist to produce a three dimensional structure in the layer of photoresist, and plasma etching the layer of photoresist and the layer of reactive mesogen to form the three dimensional structure in the layer of reactive mesogen.

Example 14

[0058] The method of Example 13, where the layer of reactive mesogen is formed by spin coating and has a substantially constant thickness prior to the plasma etching.

Example 15

[0059] The method of Example 13, where the layer of reactive mesogen is formed by printing and has a variable thickness prior to the plasma etching.

Example 16

[0060] The method of any of Examples 13-15, where forming the layer of reactive mesogen includes forming a first layer of reactive mesogen over the patterned layer of photo-alignment material and forming a second layer of reactive mesogen over the first layer of reactive mesogen.

Example 17

[0061] The method of any of Examples 13-16, where transferring the grating patterning into the layer of reactive mesogen includes self-alignment of liquid crystals within the layer of reactive mesogen.

Example 18

[0062] The method of any of Examples 13-17, where the three dimensional structure in the layer of reactive mesogen includes sloped sidewalls.

Example 19

[0063] The method of any of Examples 13-18, where the three dimensional structure in the layer of reactive mesogen includes sidewalls having a profile selected from convex, concave, and spline.

Example 20

[0064] The method of any of Examples 13-19, where the three dimensional structure in the layer of reactive mesogen has a variable thickness.

[0065] Embodiments of the present disclosure may include or be implemented in conjunction with various types of Artificial-Reality (AR) systems. AR may be any superimposed functionality and/or sensory-detectable content presented by an artificial-reality system within a user's physical surroundings. In other words, AR is a form of reality that has been adjusted in some manner before presentation to a user. AR can include and/or represent virtual reality (VR), augmented reality, mixed AR (MAR), or some combination and/or variation of these types of realities. Similarly, AR environments may include VR environments (including non-immersive, semi-immersive, and fully immersive VR environments), augmented-reality environments (including marker-based augmented-reality environments, markerless augmented-reality environments, location-based augmented-reality environments, and projection-based augmented-reality environments), hybrid-reality environments, and/or any other type or form of mixed- or alternative-reality environments.

[0066] AR content may include completely computer-generated content or computer-generated content combined with captured (e.g., real-world) content. Such AR content may include video, audio, haptic feedback, or some combination thereof, any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional (3D) effect to the viewer). Additionally, in some embodiments, AR may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., to perform activities in) an artificial reality.

[0067] AR systems may be implemented in a variety of different form factors and configurations. Some AR systems may be designed to work without near-eye displays (NEDs). Other AR systems may include a NED that also provides visibility into the real world (such as, e.g., VR system **1400** in FIGS. **14A** and **14B**). While some AR devices may be self-contained systems, other AR devices may communicate and/or coordinate with external devices to provide an AR experience to a user. Examples of such external devices include handheld controllers, mobile devices, desktop computers, devices worn by a user, devices worn by one or more other users, and/or any other suitable external system.

[0068] FIGS. **7-10B** illustrate example artificial-reality (AR) systems in accordance with some embodiments. FIG. **7** shows a first AR system **700** and first example user interactions using a wrist-wearable device **702**, a head-wearable device (e.g., AR system **1300**), and/or a handheld

intermediary processing device (HIPD) **706**. FIG. **8** shows a second AR system **800** and second example user interactions using a wrist-wearable device **802**, AR glasses **804**, and/or an HIPD **806**. FIGS. **9A** and **9B** show a third AR system **900** and third example user **908** interactions using a wrist-wearable device **902**, a head-wearable device (e.g., VR headset **950**), and/or an HIPD **906**. FIGS. **10A** and **10B** show a fourth AR system **1000** and fourth example user **1008** interactions using a wrist-wearable device **1030**, VR headset **1020**, and/or a haptic device **1060** (e.g., wearable gloves).

[0069] A wrist-wearable device **1100**, which can be used for wrist-wearable device **702**, **802**, **902**, **1030**, and one or more of its components, are described below in reference to FIGS. **11** and **12**; AR system **1300** and VR system **1400**, which can respectively be used for AR glasses **704**, **804** or VR headset **950**, **1020**, and their one or more components are described below in reference to FIGS. **13-15**.

[0070] Referring to FIG. **7**, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can communicatively couple via a network **725** (e.g., cellular, near field, Wi-Fi, personal area network, wireless LAN, etc.). Additionally, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can also communicatively couple with one or more servers **730**, computers **740** (e.g., laptops, computers, etc.), mobile devices **750** (e.g., smartphones, tablets, etc.), and/or other electronic devices via network **725** (e.g., cellular, near field, Wi-Fi, personal area network, wireless LAN, etc.).

[0071] In FIG. **7**, a user **708** is shown wearing wrist-wearable device **702** and AR glasses **704** and having HIPD **706** on their desk. The wrist-wearable device **702**, AR glasses **704**, and HIPD **706** facilitate user interaction with an AR environment. In particular, as shown by first AR system **700**, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** cause presentation of one or more avatars **710**, digital representations of contacts **712**, and virtual objects **714**. As discussed below, user **708** can interact with one or more avatars **710**, digital representations of contacts **712**, and virtual objects **714** via wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**.

[0072] User **708** can use any of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** to provide user inputs. For example, user **708** can perform one or more hand gestures that are detected by wrist-wearable device **702** (e.g., using one or more EMG sensors and/or IMUs, described below in reference to FIGS. **11** and **12**) and/or AR glasses **704** (e.g., using one or more image sensor or camera, described below in reference to FIGS. **13-10**) to provide a user input. Alternatively, or additionally, user **708** can provide a user input via one or more touch surfaces of wrist-wearable device **702**, AR glasses **704**, HIPD **706**, and/or voice commands captured by a microphone of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**. In some embodiments, wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** include a digital assistant to help user **708** in providing a user input (e.g., completing a sequence of operations, suggesting different operations or commands, providing reminders, confirming a command, etc.). In some embodiments, user **708** can provide a user input via one or more facial gestures and/or facial expressions. For example, cameras of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can track eyes of user **708** for navigating a user interface.

[0073] Wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** can operate alone or in conjunction to allow user **708** to interact with the AR environment. In some embodi-

ments, HIPD **706** is configured to operate as a central hub or control center for the wrist-wearable device **702**, AR glasses **704**, and/or another communicatively coupled device. For example, user **708** can provide an input to interact with the AR environment at any of wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**, and HIPD **706** can identify one or more back-end and front-end tasks to cause the performance of the requested interaction and distribute instructions to cause the performance of the one or more back-end and front-end tasks at wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706**. In some embodiments, a back-end task is a background processing task that is not perceptible by the user (e.g., rendering content, decompression, compression, etc.), and a front-end task is a user-facing task that is perceptible to the user (e.g., presenting information to the user, providing feedback to the user, etc.). As described below, HIPD **706** can perform the back-end tasks and provide wrist-wearable device **702** and/or AR glasses **704** operational data corresponding to the performed back-end tasks such that wrist-wearable device **702** and/or AR glasses **704** can perform the front-end tasks. In this way, HIPD **706**, which has more computational resources and greater thermal headroom than wrist-wearable device **702** and/or AR glasses **704**, performs computationally intensive tasks and reduces the computer resource utilization and/or power usage of wrist-wearable device **702** and/or AR glasses **704**.

[0074] In the example shown by first AR system **700**, HIPD **706** identifies one or more back-end tasks and front-end tasks associated with a user request to initiate an AR video call with one or more other users (represented by avatar **710** and the digital representation of contact **712**) and distributes instructions to cause the performance of the one or more back-end tasks and front-end tasks. In particular, HIPD **706** performs back-end tasks for processing and/or rendering image data (and other data) associated with the AR video call and provides operational data associated with the performed back-end tasks to AR glasses **704** such that the AR glasses **704** perform front-end tasks for presenting the AR video call (e.g., presenting avatar **710** and digital representation of contact **712**).

[0075] In some embodiments, HIPD **706** can operate as a focal or anchor point for causing the presentation of information. This allows user **708** to be generally aware of where information is presented. For example, as shown in first AR system **700**, avatar **710** and the digital representation of contact **712** are presented above HIPD **706**. In particular, HIPD **706** and AR glasses **704** operate in conjunction to determine a location for presenting avatar **710** and the digital representation of contact **712**. In some embodiments, information can be presented a predetermined distance from HIPD **706** (e.g., within 5 meters). For example, as shown in first AR system **700**, virtual object **714** is presented on the desk some distance from HIPD **706**. Similar to the above example, HIPD **706** and AR glasses **704** can operate in conjunction to determine a location for presenting virtual object **714**. Alternatively, in some embodiments, presentation of information is not bound by HIPD **706**. More specifically, avatar **710**, digital representation of contact **712**, and virtual object **714** do not have to be presented within a predetermined distance of HIPD **706**.

[0076] User inputs provided at wrist-wearable device **702**, AR glasses **704**, and/or HIPD **706** are coordinated such that the user can use any device to initiate, continue, and/or

complete an operation. For example, user **708** can provide a user input to AR glasses **704** to cause AR glasses **704** to present virtual object **714** and, while virtual object **714** is presented by AR glasses **704**, user **708** can provide one or more hand gestures via wrist-wearable device **702** to interact and/or manipulate virtual object **714**.

[0077] FIG. **8** shows a user **808** wearing a wrist-wearable device **802** and AR glasses **804**, and holding an HIPD **806**. In second AR system **800**, the wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** are used to receive and/or provide one or more messages to a contact of user **808**. In particular, wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** detect and coordinate one or more user inputs to initiate a messaging application and prepare a response to a received message via the messaging application.

[0078] In some embodiments, user **808** initiates, via a user input, an application on wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** that causes the application to initiate on at least one device. For example, in second AR system **800**, user **808** performs a hand gesture associated with a command for initiating a messaging application (represented by messaging user interface **816**), wrist-wearable device **802** detects the hand gesture and, based on a determination that user **808** is wearing AR glasses **804**, causes AR glasses **804** to present a messaging user interface **816** of the messaging application. AR glasses **804** can present messaging user interface **816** to user **808** via its display (e.g., as shown by a field of view **818** of user **808**). In some embodiments, the application is initiated and executed on the device (e.g., wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806**) that detects the user input to initiate the application, and the device provides another device operational data to cause the presentation of the messaging application. For example, wrist-wearable device **802** can detect the user input to initiate a messaging application, initiate and run the messaging application, and provide operational data to AR glasses **804** and/or HIPD **806** to cause presentation of the messaging application. Alternatively, the application can be initiated and executed at a device other than the device that detected the user input. For example, wrist-wearable device **802** can detect the hand gesture associated with initiating the messaging application and cause HIPD **806** to run the messaging application and coordinate the presentation of the messaging application.

[0079] Further, user **808** can provide a user input provided at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to continue and/or complete an operation initiated at another device. For example, after initiating the messaging application via wrist-wearable device **802** and while AR glasses **804** present messaging user interface **816**, user **808** can provide an input at HIPD **806** to prepare a response (e.g., shown by the swipe gesture performed on HIPD **806**). Gestures performed by user **808** on HIPD **806** can be provided and/or displayed on another device. For example, a swipe gesture performed on HIPD **806** is displayed on a virtual keyboard of messaging user interface **816** displayed by AR glasses **804**.

[0080] In some embodiments, wrist-wearable device **802**, AR glasses **804**, HIPD **806**, and/or any other communicatively coupled device can present one or more notifications to user **808**. The notification can be an indication of a new message, an incoming call, an application update, a status update, etc. User **808** can select the notification via wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** and

can cause presentation of an application or operation associated with the notification on at least one device. For example, user **808** can receive a notification that a message was received at wrist-wearable device **802**, AR glasses **804**, HIPD **806**, and/or any other communicatively coupled device and can then provide a user input at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to review the notification, and the device detecting the user input can cause an application associated with the notification to be initiated and/or presented at wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806**.

[0081] While the above example describes coordinated inputs used to interact with a messaging application, user inputs can be coordinated to interact with any number of applications including, but not limited to, gaming applications, social media applications, camera applications, web-based applications, financial applications, etc. For example, AR glasses **804** can present to user **808** game application data, and HIPD **806** can be used as a controller to provide inputs to the game. Similarly, user **808** can use wrist-wearable device **802** to initiate a camera of AR glasses **804**, and user **808** can use wrist-wearable device **802**, AR glasses **804**, and/or HIPD **806** to manipulate the image capture (e.g., zoom in or out, apply filters, etc.) and capture image data.

[0082] Users may interact with the devices disclosed herein in a variety of ways. For example, as shown in FIGS. **9A** and **9B**, a user **908** may interact with an AR system **900** by donning a VR headset **950** while holding HIPD **906** and wearing wrist-wearable device **902**. In this example, AR system **900** may enable a user to interact with a game **910** by swiping their arm. One or more of VR headset **950**, HIPD **906**, and wrist-wearable device **902** may detect this gesture and, in response, may display a sword strike in game **910**. Similarly, in FIGS. **10A** and **10B**, a user **1008** may interact with an AR system **1000** by donning a VR headset **1020** while wearing haptic device **1060** and wrist-wearable device **1030**. In this example, AR system **1000** may enable a user to interact with a game **1010** by swiping their arm. One or more of VR headset **1020**, haptic device **1060**, and wrist-wearable device **1030** may detect this gesture and, in response, may display a spell being cast in game **910**.

[0083] Having discussed example AR systems, devices for interacting with such AR systems and other computing systems more generally will now be discussed in greater detail. Some explanations of devices and components that can be included in some or all of the example devices discussed below are explained herein for ease of reference. Certain types of the components described below may be more suitable for a particular set of devices, and less suitable for a different set of devices. But subsequent reference to the components explained here should be considered to be encompassed by the descriptions provided.

[0084] In some embodiments discussed below, example devices and systems, including electronic devices and systems, will be addressed. Such example devices and systems are not intended to be limiting, and one of skill in the art will understand that alternative devices and systems to the example devices and systems described herein may be used to perform the operations and construct the systems and devices that are described herein.

[0085] An electronic device may be a device that uses electrical energy to perform a specific function. An electronic device can be any physical object that contains electronic components such as transistors, resistors, capaci-

tors, diodes, and integrated circuits. Examples of electronic devices include smartphones, laptops, digital cameras, televisions, gaming consoles, and music players, as well as the example electronic devices discussed herein. As described herein, an intermediary electronic device may be a device that sits between two other electronic devices and/or a subset of components of one or more electronic devices and facilitates communication, data processing, and/or data transfer between the respective electronic devices and/or electronic components.

[0086] An integrated circuit may be an electronic device made up of multiple interconnected electronic components such as transistors, resistors, and capacitors. These components may be etched onto a small piece of semiconductor material, such as silicon. Integrated circuits may include analog integrated circuits, digital integrated circuits, mixed signal integrated circuits, and/or any other suitable type or form of integrated circuit. Examples of integrated circuits include application-specific integrated circuits (ASICs), processing units, central processing units (CPUs), co-processors, and accelerators.

[0087] Analog integrated circuits, such as sensors, power management circuits, and operational amplifiers, may process continuous signals and perform analog functions such as amplification, active filtering, demodulation, and mixing. Examples of analog integrated circuits include linear integrated circuits and radio frequency circuits.

[0088] Digital integrated circuits, which may be referred to as logic integrated circuits, may include microprocessors, microcontrollers, memory chips, interfaces, power management circuits, programmable devices, and/or any other suitable type or form of integrated circuit. In some embodiments, examples of integrated circuits include central processing units (CPUs),

[0089] Processing units, such as CPUs, may be electronic components that are responsible for executing instructions and controlling the operation of an electronic device (e.g., a computer). There are various types of processors that may be used interchangeably, or may be specifically required, by embodiments described herein. For example, a processor may be: (i) a general processor designed to perform a wide range of tasks, such as running software applications, managing operating systems, and performing arithmetic and logical operations; (ii) a microcontroller designed for specific tasks such as controlling electronic devices, sensors, and motors; (iii) an accelerator, such as a graphics processing unit (GPU), designed to accelerate the creation and rendering of images, videos, and animations (e.g., virtual-reality animations, such as three-dimensional modeling); (iv) a field-programmable gate array (FPGA) that can be programmed and reconfigured after manufacturing and/or can be customized to perform specific tasks, such as signal processing, cryptography, and machine learning; and/or (v) a digital signal processor (DSP) designed to perform mathematical operations on signals such as audio, video, and radio waves. One or more processors of one or more electronic devices may be used in various embodiments described herein.

[0090] Memory generally refers to electronic components in a computer or electronic device that store data and instructions for the processor to access and manipulate. Examples of memory can include: (i) random access memory (RAM) configured to store data and instructions temporarily; (ii) read-only memory (ROM) configured to

store data and instructions permanently (e.g., one or more portions of system firmware, and/or boot loaders) and/or semi-permanently; (iii) flash memory, which can be configured to store data in electronic devices (e.g., USB drives, memory cards, and/or solid-state drives (SSDs)); and/or (iv) cache memory configured to temporarily store frequently accessed data and instructions. Memory, as described herein, can store structured data (e.g., SQL databases, MongoDB databases, GraphQL data, JSON data, etc.). Other examples of data stored in memory can include (i) profile data, including user account data, user settings, and/or other user data stored by the user, (ii) sensor data detected and/or otherwise obtained by one or more sensors, (iii) media content data including stored image data, audio data, documents, and the like, (iv) application data, which can include data collected and/or otherwise obtained and stored during use of an application, and/or any other types of data described herein.

[0091] Controllers may be electronic components that manage and coordinate the operation of other components within an electronic device (e.g., controlling inputs, processing data, and/or generating outputs). Examples of controllers can include: (i) microcontrollers, including small, low-power controllers that are commonly used in embedded systems and Internet of Things (IoT) devices; (ii) programmable logic controllers (PLCs) that may be configured to be used in industrial automation systems to control and monitor manufacturing processes; (iii) system-on-a-chip (SoC) controllers that integrate multiple components such as processors, memory, I/O interfaces, and other peripherals into a single chip; and/or (iv) DSPs.

[0092] A power system of an electronic device may be configured to convert incoming electrical power into a form that can be used to operate the device. A power system can include various components, such as (i) a power source, which can be an alternating current (AC) adapter or a direct current (DC) adapter power supply, (ii) a charger input, which can be configured to use a wired and/or wireless connection (which may be part of a peripheral interface, such as a USB, micro-USB interface, near-field magnetic coupling, magnetic inductive and magnetic resonance charging, and/or radio frequency (RF) charging), (iii) a power-management integrated circuit, configured to distribute power to various components of the device and to ensure that the device operates within safe limits (e.g., regulating voltage, controlling current flow, and/or managing heat dissipation), and/or (iv) a battery configured to store power to provide usable power to components of one or more electronic devices.

[0093] Peripheral interfaces may be electronic components (e.g., of electronic devices) that allow electronic devices to communicate with other devices or peripherals and can provide the ability to input and output data and signals. Examples of peripheral interfaces can include (i) universal serial bus (USB) and/or micro-USB interfaces configured for connecting devices to an electronic device, (ii) Bluetooth interfaces configured to allow devices to communicate with each other, including Bluetooth low energy (BLE), (iii) near field communication (NFC) interfaces configured to be short-range wireless interfaces for operations such as access control, (iv) POGO pins, which may be small, spring-loaded pins configured to provide a charging interface, (v) wireless charging interfaces, (vi) GPS

interfaces, (vii) Wi-Fi interfaces for providing a connection between a device and a wireless network, and/or (viii) sensor interfaces.

[0094] Sensors may be electronic components (e.g., in and/or otherwise in electronic communication with electronic devices, such as wearable devices) configured to detect physical and environmental changes and generate electrical signals. Examples of sensors can include (i) imaging sensors for collecting imaging data (e.g., including one or more cameras disposed on a respective electronic device), (ii) biopotential-signal sensors, (iii) inertial measurement units (e.g., IMUs) for detecting, for example, angular rate, force, magnetic field, and/or changes in acceleration, (iv) heart rate sensors for measuring a user's heart rate, (v) SpO₂ sensors for measuring blood oxygen saturation and/or other biometric data of a user, (vi) capacitive sensors for detecting changes in potential at a portion of a user's body (e.g., a sensor-skin interface), and/or (vii) light sensors (e.g., time-of-flight sensors, infrared light sensors, visible light sensors, etc.).

[0095] Biopotential-signal-sensing components may be devices used to measure electrical activity within the body (e.g., biopotential-signal sensors). Some types of biopotential-signal sensors include (i) electroencephalography (EEG) sensors configured to measure electrical activity in the brain to diagnose neurological disorders, (ii) electrocardiogram sensors configured to measure electrical activity of the heart to diagnose heart problems, (iii) electromyography (EMG) sensors configured to measure the electrical activity of muscles and to diagnose neuromuscular disorders, and (iv) electrooculography (EOG) sensors configured to measure the electrical activity of eye muscles to detect eye movement and diagnose eye disorders.

[0096] An application stored in memory of an electronic device (e.g., software) may include instructions stored in the memory. Examples of such applications include (i) games, (ii) word processors, (iii) messaging applications, (iv) media-streaming applications, (v) financial applications, (vi) calendars, (vii) clocks, and (viii) communication interface modules for enabling wired and/or wireless connections between different respective electronic devices (e.g., IEEE 1302.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, or MiWi), custom or standard wired protocols (e.g., Ethernet or HomePlug), and/or any other suitable communication protocols).

[0097] A communication interface may be a mechanism that enables different systems or devices to exchange information and data with each other, including hardware, software, or a combination of both hardware and software. For example, a communication interface can refer to a physical connector and/or port on a device that enables communication with other devices (e.g., USB, Ethernet, HDMI, Bluetooth). In some embodiments, a communication interface can refer to a software layer that enables different software programs to communicate with each other (e.g., application programming interfaces (APIs), protocols like HTTP and TCP/IP, etc.).

[0098] A graphics module may be a component or software module that is designed to handle graphical operations and/or processes and can include a hardware module and/or a software module.

[0099] Non-transitory computer-readable storage media may be physical devices or storage media that can be used

to store electronic data in a non-transitory form (e.g., such that the data is stored permanently until it is intentionally deleted or modified).

[0100] FIGS. 11 and 12 illustrate an example wrist-wearable device 1100 and an example computer system 1200, in accordance with some embodiments. Wrist-wearable device 1100 is an instance of wearable device 702 described in FIG. 7 herein, such that the wearable device 702 should be understood to have the features of the wrist-wearable device 1100 and vice versa. FIG. 12 illustrates components of the wrist-wearable device 1100, which can be used individually or in combination, including combinations that include other electronic devices and/or electronic components.

[0101] FIG. 11 shows a wearable band 1110 and a watch body 1120 (or capsule) being coupled, as discussed below, to form wrist-wearable device 1100. Wrist-wearable device 1100 can perform various functions and/or operations associated with navigating through user interfaces and selectively opening applications as well as the functions and/or operations described above with reference to FIGS. 7-10B.

[0102] As will be described in more detail below, operations executed by wrist-wearable device 1100 can include (i) presenting content to a user (e.g., displaying visual content via a display 1105), (ii) detecting (e.g., sensing) user input (e.g., sensing a touch on peripheral button 1123 and/or at a touch screen of the display 1105, a hand gesture detected by sensors (e.g., biopotential sensors)), (iii) sensing biometric data (e.g., neuromuscular signals, heart rate, temperature, sleep, etc.) via one or more sensors 1113, messaging (e.g., text, speech, video, etc.); image capture via one or more imaging devices or cameras 1125, wireless communications (e.g., cellular, near field, Wi-Fi, personal area network, etc.), location determination, financial transactions, providing haptic feedback, providing alarms, providing notifications, providing biometric authentication, providing health monitoring, providing sleep monitoring, etc.

[0103] The above-example functions can be executed independently in watch body 1120, independently in wearable band 1110, and/or via an electronic communication between watch body 1120 and wearable band 1110. In some embodiments, functions can be executed on wrist-wearable device 1100 while an AR environment is being presented (e.g., via one of AR systems 700 to 1000). The wearable devices described herein can also be used with other types of AR environments.

[0104] Wearable band 1110 can be configured to be worn by a user such that an inner surface of a wearable structure 1111 of wearable band 1110 is in contact with the user's skin. In this example, when worn by a user, sensors 1113 may contact the user's skin. In some examples, one or more of sensors 1113 can sense biometric data such as a user's heart rate, a saturated oxygen level, temperature, sweat level, neuromuscular signals, or a combination thereof. One or more of sensors 1113 can also sense data about a user's environment including a user's motion, altitude, location, orientation, gait, acceleration, position, or a combination thereof. In some embodiment, one or more of sensors 1113 can be configured to track a position and/or motion of wearable band 1110. One or more of sensors 1113 can include any of the sensors defined above and/or discussed below with respect to FIG. 11.

[0105] One or more of sensors 1113 can be distributed on an inside and/or an outside surface of wearable band 1110. In some embodiments, one or more of sensors 1113 are

uniformly spaced along wearable band **1110**. Alternatively, in some embodiments, one or more of sensors **1113** are positioned at distinct points along wearable band **1110**. As shown in FIG. **11**, one or more of sensors **1113** can be the same or distinct. For example, in some embodiments, one or more of sensors **1113** can be shaped as a pill (e.g., sensor **1113a**), an oval, a circle a square, an oblong (e.g., sensor **1113c**) and/or any other shape that maintains contact with the user's skin (e.g., such that neuromuscular signal and/or other biometric data can be accurately measured at the user's skin). In some embodiments, one or more sensors of **1113** are aligned to form pairs of sensors (e.g., for sensing neuromuscular signals based on differential sensing within each respective sensor). For example, sensor **1113b** may be aligned with an adjacent sensor to form sensor pair **1114a** and sensor **1113d** may be aligned with an adjacent sensor to form sensor pair **1114b**. In some embodiments, wearable band **1110** does not have a sensor pair. Alternatively, in some embodiments, wearable band **1110** has a predetermined number of sensor pairs (one pair of sensors, three pairs of sensors, four pairs of sensors, six pairs of sensors, sixteen pairs of sensors, etc.).

[0106] Wearable band **1110** can include any suitable number of sensors **1113**. In some embodiments, the number and arrangement of sensors **1113** depends on the particular application for which wearable band **1110** is used. For instance, wearable band **1110** can be configured as an armband, wristband, or chest-band that include a plurality of sensors **1113** with different number of sensors **1113**, a variety of types of individual sensors with the plurality of sensors **1113**, and different arrangements for each use case, such as medical use cases as compared to gaming or general day-to-day use cases.

[0107] In accordance with some embodiments, wearable band **1110** further includes an electrical ground electrode and a shielding electrode. The electrical ground and shielding electrodes, like the sensors **1113**, can be distributed on the inside surface of the wearable band **1110** such that they contact a portion of the user's skin. For example, the electrical ground and shielding electrodes can be at an inside surface of a coupling mechanism **1116** or an inside surface of a wearable structure **1111**. The electrical ground and shielding electrodes can be formed and/or use the same components as sensors **1113**. In some embodiments, wearable band **1110** includes more than one electrical ground electrode and more than one shielding electrode.

[0108] Sensors **1113** can be formed as part of wearable structure **1111** of wearable band **1110**. In some embodiments, sensors **1113** are flush or substantially flush with wearable structure **1111** such that they do not extend beyond the surface of wearable structure **1111**. While flush with wearable structure **1111**, sensors **1113** are still configured to contact the user's skin (e.g., via a skin-contacting surface). Alternatively, in some embodiments, sensors **1113** extend beyond wearable structure **1111** a predetermined distance (e.g., 0.1-2 mm) to make contact and depress into the user's skin. In some embodiment, sensors **1113** are coupled to an actuator (not shown) configured to adjust an extension height (e.g., a distance from the surface of wearable structure **1111**) of sensors **1113** such that sensors **1113** make contact and depress into the user's skin. In some embodiments, the actuators adjust the extension height between 0.01 mm-1.2 mm. This may allow a user to customize the positioning of sensors **1113** to improve the overall comfort

of the wearable band **1110** when worn while still allowing sensors **1113** to contact the user's skin. In some embodiments, sensors **1113** are indistinguishable from wearable structure **1111** when worn by the user.

[0109] Wearable structure **1111** can be formed of an elastic material, elastomers, etc., configured to be stretched and fitted to be worn by the user. In some embodiments, wearable structure **1111** is a textile or woven fabric. As described above, sensors **1113** can be formed as part of a wearable structure **1111**. For example, sensors **1113** can be molded into the wearable structure **1111**, be integrated into a woven fabric (e.g., sensors **1113** can be sewn into the fabric and mimic the pliability of fabric and can and/or be constructed from a series woven strands of fabric).

[0110] Wearable structure **1111** can include flexible electronic connectors that interconnect sensors **1113**, the electronic circuitry, and/or other electronic components (described below in reference to FIG. **12**) that are enclosed in wearable band **1110**. In some embodiments, the flexible electronic connectors are configured to interconnect sensors **1113**, the electronic circuitry, and/or other electronic components of wearable band **1110** with respective sensors and/or other electronic components of another electronic device (e.g., watch body **1120**). The flexible electronic connectors are configured to move with wearable structure **1111** such that the user adjustment to wearable structure **1111** (e.g., resizing, pulling, folding, etc.) does not stress or strain the electrical coupling of components of wearable band **1110**.

[0111] As described above, wearable band **1110** is configured to be worn by a user. In particular, wearable band **1110** can be shaped or otherwise manipulated to be worn by a user. For example, wearable band **1110** can be shaped to have a substantially circular shape such that it can be configured to be worn on the user's lower arm or wrist. Alternatively, wearable band **1110** can be shaped to be worn on another body part of the user, such as the user's upper arm (e.g., around a bicep), forearm, chest, legs, etc. Wearable band **1110** can include a retaining mechanism **1112** (e.g., a buckle, a hook and loop fastener, etc.) for securing wearable band **1110** to the user's wrist or other body part. While wearable band **1110** is worn by the user, sensors **1113** sense data (referred to as sensor data) from the user's skin. In some examples, sensors **1113** of wearable band **1110** obtain (e.g., sense and record) neuromuscular signals.

[0112] The sensed data (e.g., sensed neuromuscular signals) can be used to detect and/or determine the user's intention to perform certain motor actions. In some examples, sensors **1113** may sense and record neuromuscular signals from the user as the user performs muscular activations (e.g., movements, gestures, etc.). The detected and/or determined motor actions (e.g., phalange (or digit) movements, wrist movements, hand movements, and/or other muscle intentions) can be used to determine control commands or control information (instructions to perform certain commands after the data is sensed) for causing a computing device to perform one or more input commands. For example, the sensed neuromuscular signals can be used to control certain user interfaces displayed on display **1105** of wrist-wearable device **1100** and/or can be transmitted to a device responsible for rendering an artificial-reality environment (e.g., a head-mounted display) to perform an action in an associated artificial-reality environment, such as to control the motion of a virtual device displayed to the user.

The muscular activations performed by the user can include static gestures, such as placing the user's hand palm down on a table, dynamic gestures, such as grasping a physical or virtual object, and covert gestures that are imperceptible to another person, such as slightly tensing a joint by co-contracting opposing muscles or using sub-muscular activations. The muscular activations performed by the user can include symbolic gestures (e.g., gestures mapped to other gestures, interactions, or commands, for example, based on a gesture vocabulary that specifies the mapping of gestures to commands).

[0113] The sensor data sensed by sensors 1113 can be used to provide a user with an enhanced interaction with a physical object (e.g., devices communicatively coupled with wearable band 1110) and/or a virtual object in an artificial-reality application generated by an artificial-reality system (e.g., user interface objects presented on the display 1105, or another computing device (e.g., a smartphone)).

[0114] In some embodiments, wearable band 1110 includes one or more haptic devices 1246 (e.g., a vibratory haptic actuator) that are configured to provide haptic feedback (e.g., a cutaneous and/or kinesthetic sensation, etc.) to the user's skin. Sensors 1113 and/or haptic devices 1246 (shown in FIG. 12) can be configured to operate in conjunction with multiple applications including, without limitation, health monitoring, social media, games, and artificial reality (e.g., the applications associated with artificial reality).

[0115] Wearable band 1110 can also include coupling mechanism 1116 for detachably coupling a capsule (e.g., a computing unit) or watch body 1120 (via a coupling surface of the watch body 1120) to wearable band 1110. For example, a cradle or a shape of coupling mechanism 1116 can correspond to shape of watch body 1120 of wrist-wearable device 1100. In particular, coupling mechanism 1116 can be configured to receive a coupling surface proximate to the bottom side of watch body 1120 (e.g., a side opposite to a front side of watch body 1120 where display 1105 is located), such that a user can push watch body 1120 downward into coupling mechanism 1116 to attach watch body 1120 to coupling mechanism 1116. In some embodiments, coupling mechanism 1116 can be configured to receive a top side of the watch body 1120 (e.g., a side proximate to the front side of watch body 1120 where display 1105 is located) that is pushed upward into the cradle, as opposed to being pushed downward into coupling mechanism 1116. In some embodiments, coupling mechanism 1116 is an integrated component of wearable band 1110 such that wearable band 1110 and coupling mechanism 1116 are a single unitary structure. In some embodiments, coupling mechanism 1116 is a type of frame or shell that allows watch body 1120 coupling surface to be retained within or on wearable band 1110 coupling mechanism 1116 (e.g., a cradle, a tracker band, a support base, a clasp, etc.).

[0116] Coupling mechanism 1116 can allow for watch body 1120 to be detachably coupled to the wearable band 1110 through a friction fit, magnetic coupling, a rotation-based connector, a shear-pin coupler, a retention spring, one or more magnets, a clip, a pin shaft, a hook and loop fastener, or a combination thereof. A user can perform any type of motion to couple the watch body 1120 to wearable band 1110 and to decouple the watch body 1120 from the wearable band 1110. For example, a user can twist, slide, turn, push, pull, or rotate watch body 1120 relative to wearable band 1110, or a combination thereof, to attach

watch body 1120 to wearable band 1110 and to detach watch body 1120 from wearable band 1110. Alternatively, as discussed below, in some embodiments, the watch body 1120 can be decoupled from the wearable band 1110 by actuation of a release mechanism 1129.

[0117] Wearable band 1110 can be coupled with watch body 1120 to increase the functionality of wearable band 1110 (e.g., converting wearable band 1110 into wrist-wearable device 1100, adding an additional computing unit and/or battery to increase computational resources and/or a battery life of wearable band 1110, adding additional sensors to improve sensed data, etc.). As described above, wearable band 1110 and coupling mechanism 1116 are configured to operate independently (e.g., execute functions independently) from watch body 1120. For example, coupling mechanism 1116 can include one or more sensors 1113 that contact a user's skin when wearable band 1110 is worn by the user, with or without watch body 1120 and can provide sensor data for determining control commands.

[0118] A user can detach watch body 1120 from wearable band 1110 to reduce the encumbrance of wrist-wearable device 1100 to the user. For embodiments in which watch body 1120 is removable, watch body 1120 can be referred to as a removable structure, such that in these embodiments wrist-wearable device 1100 includes a wearable portion (e.g., wearable band 1110) and a removable structure (e.g., watch body 1120).

[0119] Turning to watch body 1120, in some examples watch body 1120 can have a substantially rectangular or circular shape. Watch body 1120 is configured to be worn by the user on their wrist or on another body part. More specifically, watch body 1120 is sized to be easily carried by the user, attached on a portion of the user's clothing, and/or coupled to wearable band 1110 (forming the wrist-wearable device 1100). As described above, watch body 1120 can have a shape corresponding to coupling mechanism 1116 of wearable band 1110. In some embodiments, watch body 1120 includes a single release mechanism 1129 or multiple release mechanisms (e.g., two release mechanisms 1129 positioned on opposing sides of watch body 1120, such as spring-loaded buttons) for decoupling watch body 1120 from wearable band 1110. Release mechanism 1129 can include, without limitation, a button, a knob, a plunger, a handle, a lever, a fastener, a clasp, a dial, a latch, or a combination thereof.

[0120] A user can actuate release mechanism 1129 by pushing, turning, lifting, depressing, shifting, or performing other actions on release mechanism 1129. Actuation of release mechanism 1129 can release (e.g., decouple) watch body 1120 from coupling mechanism 1116 of wearable band 1110, allowing the user to use watch body 1120 independently from wearable band 1110 and vice versa. For example, decoupling watch body 1120 from wearable band 1110 can allow a user to capture images using rear-facing camera 1125b. Although release mechanism 1129 is shown positioned at a corner of watch body 1120, release mechanism 1129 can be positioned anywhere on watch body 1120 that is convenient for the user to actuate. In addition, in some embodiments, wearable band 1110 can also include a respective release mechanism for decoupling watch body 1120 from coupling mechanism 1116. In some embodiments, release mechanism 1129 is optional and watch body 1120 can be decoupled from coupling mechanism 1116 as described above (e.g., via twisting, rotating, etc.).

[0121] Watch body 1120 can include one or more peripheral buttons 1123 and 1127 for performing various operations at watch body 1120. For example, peripheral buttons 1123 and 1127 can be used to turn on or wake (e.g., transition from a sleep state to an active state) display 1105, unlock watch body 1120, increase or decrease a volume, increase or decrease a brightness, interact with one or more applications, interact with one or more user interfaces, etc. Additionally or alternatively, in some embodiments, display 1105 operates as a touch screen and allows the user to provide one or more inputs for interacting with watch body 1120.

[0122] In some embodiments, watch body 1120 includes one or more sensors 1121. Sensors 1121 of watch body 1120 can be the same or distinct from sensors 1113 of wearable band 1110. Sensors 1121 of watch body 1120 can be distributed on an inside and/or an outside surface of watch body 1120. In some embodiments, sensors 1121 are configured to contact a user's skin when watch body 1120 is worn by the user. For example, sensors 1121 can be placed on the bottom side of watch body 1120 and coupling mechanism 1116 can be a cradle with an opening that allows the bottom side of watch body 1120 to directly contact the user's skin. Alternatively, in some embodiments, watch body 1120 does not include sensors that are configured to contact the user's skin (e.g., including sensors internal and/or external to the watch body 1120 that are configured to sense data of watch body 1120 and the surrounding environment). In some embodiments, sensors 1121 are configured to track a position and/or motion of watch body 1120.

[0123] Watch body 1120 and wearable band 1110 can share data using a wired communication method (e.g., a Universal Asynchronous Receiver/Transmitter (UART), a USB transceiver, etc.) and/or a wireless communication method (e.g., near field communication, Bluetooth, etc.). For example, watch body 1120 and wearable band 1110 can share data sensed by sensors 1113 and 1121, as well as application and device specific information (e.g., active and/or available applications, output devices (e.g., displays, speakers, etc.), input devices (e.g., touch screens, microphones, imaging sensors, etc.).

[0124] In some embodiments, watch body 1120 can include, without limitation, a front-facing camera 1125a and/or a rear-facing camera 1125b, sensors 1121 (e.g., a biometric sensor, an IMU, a heart rate sensor, a saturated oxygen sensor, a neuromuscular signal sensor, an altimeter sensor, a temperature sensor, a bioimpedance sensor, a pedometer sensor, an optical sensor (e.g., imaging sensor 1263), a touch sensor, a sweat sensor, etc.). In some embodiments, watch body 1120 can include one or more haptic devices 1276 (e.g., a vibratory haptic actuator) that is configured to provide haptic feedback (e.g., a cutaneous and/or kinesthetic sensation, etc.) to the user. Sensors 1221 and/or haptic device 1276 can also be configured to operate in conjunction with multiple applications including, without limitation, health monitoring applications, social media applications, game applications, and artificial reality applications (e.g., the applications associated with artificial reality).

[0125] As described above, watch body 1120 and wearable band 1110, when coupled, can form wrist-wearable device 1100. When coupled, watch body 1120 and wearable band 1110 may operate as a single device to execute functions (operations, detections, communications, etc.)

described herein. In some embodiments, each device may be provided with particular instructions for performing the one or more operations of wrist-wearable device 1100. For example, in accordance with a determination that watch body 1120 does not include neuromuscular signal sensors, wearable band 1110 can include alternative instructions for performing associated instructions (e.g., providing sensed neuromuscular signal data to watch body 1120 via a different electronic device). Operations of wrist-wearable device 1100 can be performed by watch body 1120 alone or in conjunction with wearable band 1110 (e.g., via respective processors and/or hardware components) and vice versa. In some embodiments, operations of wrist-wearable device 1100, watch body 1120, and/or wearable band 1110 can be performed in conjunction with one or more processors and/or hardware components.

[0126] As described below with reference to the block diagram of FIG. 12, wearable band 1110 and/or watch body 1120 can each include independent resources required to independently execute functions. For example, wearable band 1110 and/or watch body 1120 can each include a power source (e.g., a battery), a memory, data storage, a processor (e.g., a central processing unit (CPU)), communications, a light source, and/or input/output devices.

[0127] FIG. 12 shows block diagrams of a computing system 1230 corresponding to wearable band 1110 and a computing system 1260 corresponding to watch body 1120 according to some embodiments. Computing system 1200 of wrist-wearable device 1100 may include a combination of components of wearable band computing system 1230 and watch body computing system 1260, in accordance with some embodiments.

[0128] Watch body 1120 and/or wearable band 1110 can include one or more components shown in watch body computing system 1260. In some embodiments, a single integrated circuit may include all or a substantial portion of the components of watch body computing system 1260 included in a single integrated circuit. Alternatively, in some embodiments, components of the watch body computing system 1260 may be included in a plurality of integrated circuits that are communicatively coupled. In some embodiments, watch body computing system 1260 may be configured to couple (e.g., via a wired or wireless connection) with wearable band computing system 1230, which may allow the computing systems to share components, distribute tasks, and/or perform other operations described herein (individually or as a single device).

[0129] Watch body computing system 1260 can include one or more processors 1279, a controller 1277, a peripherals interface 1261, a power system 1295, and memory (e.g., a memory 1280).

[0130] Power system 1295 can include a charger input 1296, a power-management integrated circuit (PMIC) 1297, and a battery 1298. In some embodiments, a watch body 1120 and a wearable band 1110 can have respective batteries (e.g., battery 1298 and 1259) and can share power with each other. Watch body 1120 and wearable band 1110 can receive a charge using a variety of techniques. In some embodiments, watch body 1120 and wearable band 1110 can use a wired charging assembly (e.g., power cords) to receive the charge. Alternatively, or in addition, watch body 1120 and/or wearable band 1110 can be configured for wireless charging. For example, a portable charging device can be designed to mate with a portion of watch body 1120 and/or wearable

band 1110 and wirelessly deliver usable power to battery 1298 of watch body 1120 and/or battery 1259 of wearable band 1110. Watch body 1120 and wearable band 1110 can have independent power systems (e.g., power system 1295 and 1256, respectively) to enable each to operate independently. Watch body 1120 and wearable band 1110 can also share power (e.g., one can charge the other) via respective PMICs (e.g., PMICs 1297 and 1258) and charger inputs (e.g., 1257 and 1296) that can share power over power and ground conductors and/or over wireless charging antennas.

[0131] In some embodiments, peripherals interface 1261 can include one or more sensors 1221. Sensors 1221 can include one or more coupling sensors 1262 for detecting when watch body 1120 is coupled with another electronic device (e.g., a wearable band 1110). Sensors 1221 can include one or more imaging sensors 1263 (e.g., one or more of cameras 1225, and/or separate imaging sensors 1263 (e.g., thermal-imaging sensors)). In some embodiments, sensors 1221 can include one or more SpO2 sensors 1264. In some embodiments, sensors 1221 can include one or more biopotential-signal sensors (e.g., EMG sensors 1265, which may be disposed on an interior, user-facing portion of watch body 1120 and/or wearable band 1110). In some embodiments, sensors 1221 may include one or more capacitive sensors 1266. In some embodiments, sensors 1221 may include one or more heart rate sensors 1267. In some embodiments, sensors 1221 may include one or more IMU sensors 1268. In some embodiments, one or more IMU sensors 1268 can be configured to detect movement of a user's hand or other location where watch body 1120 is placed or held.

[0132] In some embodiments, one or more of sensors 1221 may provide an example human-machine interface. For example, a set of neuromuscular sensors, such as EMG sensors 1265, may be arranged circumferentially around wearable band 1110 with an interior surface of EMG sensors 1265 being configured to contact a user's skin. Any suitable number of neuromuscular sensors may be used (e.g., between 2 and 20 sensors). The number and arrangement of neuromuscular sensors may depend on the particular application for which the wearable device is used. For example, wearable band 1110 can be used to generate control information for controlling an augmented reality system, a robot, controlling a vehicle, scrolling through text, controlling a virtual avatar, or any other suitable control task.

[0133] In some embodiments, neuromuscular sensors may be coupled together using flexible electronics incorporated into the wireless device, and the output of one or more of the sensing components can be optionally processed using hardware signal processing circuitry (e.g., to perform amplification, filtering, and/or rectification). In other embodiments, at least some signal processing of the output of the sensing components can be performed in software such as processors 1279. Thus, signal processing of signals sampled by the sensors can be performed in hardware, software, or by any suitable combination of hardware and software, as aspects of the technology described herein are not limited in this respect.

[0134] Neuromuscular signals may be processed in a variety of ways. For example, the output of EMG sensors 1265 may be provided to an analog front end, which may be configured to perform analog processing (e.g., amplification, noise reduction, filtering, etc.) on the recorded signals. The processed analog signals may then be provided to an analog-

to-digital converter, which may convert the analog signals to digital signals that can be processed by one or more computer processors. Furthermore, although this example is as discussed in the context of interfaces with EMG sensors, the embodiments described herein can also be implemented in wearable interfaces with other types of sensors including, but not limited to, mechanomyography (MMG) sensors, sonomyography (SMG) sensors, and electrical impedance tomography (EIT) sensors.

[0135] In some embodiments, peripherals interface 1261 includes a near-field communication (NFC) component 1269, a global-position system (GPS) component 1270, a long-term evolution (LTE) component 1271, and/or a Wi-Fi and/or Bluetooth communication component 1272. In some embodiments, peripherals interface 1261 includes one or more buttons 1273 (e.g., peripheral buttons 1123 and 1127 in FIG. 11), which, when selected by a user, cause operation to be performed at watch body 1120. In some embodiments, the peripherals interface 1261 includes one or more indicators, such as a light emitting diode (LED), to provide a user with visual indicators (e.g., message received, low battery, active microphone and/or camera, etc.).

[0136] Watch body 1120 can include at least one display 1105 for displaying visual representations of information or data to a user, including user-interface elements and/or three-dimensional virtual objects. The display can also include a touch screen for inputting user inputs, such as touch gestures, swipe gestures, and the like. Watch body 1120 can include at least one speaker 1274 and at least one microphone 1275 for providing audio signals to the user and receiving audio input from the user. The user can provide user inputs through microphone 1275 and can also receive audio output from speaker 1274 as part of a haptic event provided by haptic controller 1278. Watch body 1120 can include at least one camera 1225, including a front camera 1225a and a rear camera 1225b. Cameras 1225 can include ultra-wide-angle cameras, wide angle cameras, fish-eye cameras, spherical cameras, telephoto cameras, depth-sensing cameras, or other types of cameras.

[0137] Watch body computing system 1260 can include one or more haptic controllers 1278 and associated componentry (e.g., haptic devices 1276) for providing haptic events at watch body 1120 (e.g., a vibrating sensation or audio output in response to an event at the watch body 1120). Haptic controllers 1278 can communicate with one or more haptic devices 1276, such as electroacoustic devices, including a speaker of the one or more speakers 1274 and/or other audio components and/or electromechanical devices that convert energy into linear motion such as a motor, solenoid, electroactive polymer, piezoelectric actuator, electrostatic actuator, or other tactile output generating components (e.g., a component that converts electrical signals into tactile outputs on the device). Haptic controller 1278 can provide haptic events to that are capable of being sensed by a user of watch body 1120. In some embodiments, one or more haptic controllers 1278 can receive input signals from an application of applications 1282.

[0138] In some embodiments, wearable band computing system 1230 and/or watch body computing system 1260 can include memory 1280, which can be controlled by one or more memory controllers of controllers 1277. In some embodiments, software components stored in memory 1280 include one or more applications 1282 configured to perform operations at the watch body 1120. In some embodiments,

one or more applications **1282** may include games, word processors, messaging applications, calling applications, web browsers, social media applications, media streaming applications, financial applications, calendars, clocks, etc. In some embodiments, software components stored in memory **1280** include one or more communication interface modules **1283** as defined above. In some embodiments, software components stored in memory **1280** include one or more graphics modules **1284** for rendering, encoding, and/or decoding audio and/or visual data and one or more data management modules **1285** for collecting, organizing, and/or providing access to data **1287** stored in memory **1280**. In some embodiments, one or more of applications **1282** and/or one or more modules can work in conjunction with one another to perform various tasks at the watch body **1120**.

[0139] In some embodiments, software components stored in memory **1280** can include one or more operating systems **1281** (e.g., a Linux-based operating system, an Android operating system, etc.). Memory **1280** can also include data **1287**. Data **1287** can include profile data **1288A**, sensor data **1289A**, media content data **1290**, and application data **1291**.

[0140] It should be appreciated that watch body computing system **1260** is an example of a computing system within watch body **1120**, and that watch body **1120** can have more or fewer components than shown in watch body computing system **1260**, can combine two or more components, and/or can have a different configuration and/or arrangement of the components. The various components shown in watch body computing system **1260** are implemented in hardware, software, firmware, or a combination thereof, including one or more signal processing and/or application-specific integrated circuits.

[0141] Turning to the wearable band computing system **1230**, one or more components that can be included in wearable band **1110** are shown. Wearable band computing system **1230** can include more or fewer components than shown in watch body computing system **1260**, can combine two or more components, and/or can have a different configuration and/or arrangement of some or all of the components. In some embodiments, all, or a substantial portion of the components of wearable band computing system **1230** are included in a single integrated circuit. Alternatively, in some embodiments, components of wearable band computing system **1230** are included in a plurality of integrated circuits that are communicatively coupled. As described above, in some embodiments, wearable band computing system **1230** is configured to couple (e.g., via a wired or wireless connection) with watch body computing system **1260**, which allows the computing systems to share components, distribute tasks, and/or perform other operations described herein (individually or as a single device).

[0142] Wearable band computing system **1230**, similar to watch body computing system **1260**, can include one or more processors **1249**, one or more controllers **1247** (including one or more haptics controllers **1248**), a peripherals interface **1231** that can include one or more sensors **1213** and other peripheral devices, a power source (e.g., a power system **1256**), and memory (e.g., a memory **1250**) that includes an operating system (e.g., an operating system **1251**), data (e.g., data **1254** including profile data **1288B**, sensor data **1289B**, etc.), and one or more modules (e.g., a communications interface module **1252**, a data management module **1253**, etc.).

[0143] One or more of sensors **1213** can be analogous to sensors **1221** of watch body computing system **1260**. For example, sensors **1213** can include one or more coupling sensors **1232**, one or more SpO₂ sensors **1234**, one or more EMG sensors **1235**, one or more capacitive sensors **1236**, one or more heart rate sensors **1237**, and one or more IMU sensors **1238**.

[0144] Peripherals interface **1231** can also include other components analogous to those included in peripherals interface **1261** of watch body computing system **1260**, including an NFC component **1239**, a GPS component **1240**, an LTE component **1241**, a Wi-Fi and/or Bluetooth communication component **1242**, and/or one or more haptic devices **1246** as described above in reference to peripherals interface **1261**. In some embodiments, peripherals interface **1231** includes one or more buttons **1243**, a display **1233**, a speaker **1244**, a microphone **1245**, and a camera **1255**. In some embodiments, peripherals interface **1231** includes one or more indicators, such as an LED.

[0145] It should be appreciated that wearable band computing system **1230** is an example of a computing system within wearable band **1110**, and that wearable band **1110** can have more or fewer components than shown in wearable band computing system **1230**, combine two or more components, and/or have a different configuration and/or arrangement of the components. The various components shown in wearable band computing system **1230** can be implemented in one or more of a combination of hardware, software, or firmware, including one or more signal processing and/or application-specific integrated circuits.

[0146] Wrist-wearable device **1100** with respect to FIG. 11 is an example of wearable band **1110** and watch body **1120** coupled together, so wrist-wearable device **1100** will be understood to include the components shown and described for wearable band computing system **1230** and watch body computing system **1260**. In some embodiments, wrist-wearable device **1100** has a split architecture (e.g., a split mechanical architecture, a split electrical architecture, etc.) between watch body **1120** and wearable band **1110**. In other words, all of the components shown in wearable band computing system **1230** and watch body computing system **1260** can be housed or otherwise disposed in a combined wrist-wearable device **1100** or within individual components of watch body **1120**, wearable band **1110**, and/or portions thereof (e.g., a coupling mechanism **1116** of wearable band **1110**).

[0147] The techniques described above can be used with any device for sensing neuromuscular signals but could also be used with other types of wearable devices for sensing neuromuscular signals (such as body-wearable or head-wearable devices that might have neuromuscular sensors closer to the brain or spinal column).

[0148] In some embodiments, wrist-wearable device **1100** can be used in conjunction with a head-wearable device (e.g., AR system **1300** and VR system **1400**) and/or an HIPD, and wrist-wearable device **1100** can also be configured to be used to allow a user to control any aspect of the artificial reality (e.g., by using EMG-based gestures to control user interface objects in the artificial reality and/or by allowing a user to interact with the touchscreen on the wrist-wearable device to also control aspects of the artificial reality). Having thus described example wrist-wearable

devices, attention will now be turned to example head-wearable devices, such as AR system **1300** and VR system **1400**.

[0149] FIGS. **13** to **15** show example artificial-reality systems, which can be used as or in connection with wrist-wearable device **1100**. In some embodiments, AR system **1300** includes an eyewear device **1302**, as shown in FIG. **13**. In some embodiments, VR system **1400** includes a head-mounted display (HMD) **1412**, as shown in FIGS. **14A** and **14B**. In some embodiments, AR system **1300** and VR system **1400** can include one or more analogous components (e.g., components for presenting interactive artificial-reality environments, such as processors, memory, and/or presentation devices, including one or more displays and/or one or more waveguides), some of which are described in more detail with respect to FIG. **15**. As described herein, a head-wearable device can include components of eyewear device **1302** and/or head-mounted display **1412**. Some embodiments of head-wearable devices do not include any displays, including any of the displays described with respect to AR system **1300** and/or VR system **1400**. While the example artificial-reality systems are respectively described herein as AR system **1300** and VR system **1400**, either or both of the example AR systems described herein can be configured to present fully-immersive virtual-reality scenes presented in substantially all of a user's field of view or subtler augmented-reality scenes that are presented within a portion, less than all, of the user's field of view.

[0150] FIG. **13** show an example visual depiction of AR system **1300**, including an eyewear device **1302** (which may also be described herein as augmented-reality glasses, and/or smart glasses). AR system **1300** can include additional electronic components that are not shown in FIG. **13**, such as a wearable accessory device and/or an intermediary processing device, in electronic communication or otherwise configured to be used in conjunction with the eyewear device **1302**. In some embodiments, the wearable accessory device and/or the intermediary processing device may be configured to couple with eyewear device **1302** via a coupling mechanism in electronic communication with a coupling sensor **1524** (FIG. **15**), where coupling sensor **1524** can detect when an electronic device becomes physically or electronically coupled with eyewear device **1302**. In some embodiments, eyewear device **1302** can be configured to couple to a housing **1590** (FIG. **15**), which may include one or more additional coupling mechanisms configured to couple with additional accessory devices. The components shown in FIG. **13** can be implemented in hardware, software, firmware, or a combination thereof, including one or more signal-processing components and/or application-specific integrated circuits (ASICs).

[0151] Eyewear device **1302** includes mechanical glasses components, including a frame **1304** configured to hold one or more lenses (e.g., one or both lenses **1306-1** and **1306-2**). One of ordinary skill in the art will appreciate that eyewear device **1302** can include additional mechanical components, such as hinges configured to allow portions of frame **1304** of eyewear device **1302** to be folded and unfolded, a bridge configured to span the gap between lenses **1306-1** and **1306-2** and rest on the user's nose, nose pads configured to rest on the bridge of the nose and provide support for eyewear device **1302**, earpieces configured to rest on the user's ears and provide additional support for eyewear device **1302**, temple arms configured to extend from the

hinges to the earpieces of eyewear device **1302**, and the like. One of ordinary skill in the art will further appreciate that some examples of AR system **1300** can include none of the mechanical components described herein. For example, smart contact lenses configured to present artificial reality to users may not include any components of eyewear device **1302**.

[0152] Eyewear device **1302** includes electronic components, many of which will be described in more detail below with respect to FIG. **10**. Some example electronic components are illustrated in FIG. **13**, including acoustic sensors **1325-1**, **1325-2**, **1325-3**, **1325-4**, **1325-5**, and **1325-6**, which can be distributed along a substantial portion of the frame **1304** of eyewear device **1302**. Eyewear device **1302** also includes a left camera **1339A** and a right camera **1339B**, which are located on different sides of the frame **1304**. Eyewear device **1302** also includes a processor **1348** (or any other suitable type or form of integrated circuit) that is embedded into a portion of the frame **1304**.

[0153] FIGS. **14A** and **14B** show a VR system **1400** that includes a head-mounted display (HMD) **1412** (e.g., also referred to herein as an artificial-reality headset, a head-wearable device, a VR headset, etc.), in accordance with some embodiments. As noted, some artificial-reality systems (e.g., AR system **1300**) may, instead of blending an artificial reality with actual reality, substantially replace one or more of a user's visual and/or other sensory perceptions of the real world with a virtual experience (e.g., AR systems **900** and **1000**).

[0154] HMD **1412** includes a front body **1414** and a frame **1416** (e.g., a strap or band) shaped to fit around a user's head. In some embodiments, front body **1414** and/or frame **1416** include one or more electronic elements for facilitating presentation of and/or interactions with an AR and/or VR system (e.g., displays, IMUs, tracking emitter or detectors). In some embodiments, HMD **1412** includes output audio transducers (e.g., an audio transducer **1418**), as shown in FIG. **14B**. In some embodiments, one or more components, such as the output audio transducer(s) **1418** and frame **1416**, can be configured to attach and detach (e.g., are detachably attachable) to HMD **1412** (e.g., a portion or all of frame **1416**, and/or audio transducer **1418**), as shown in FIG. **14B**. In some embodiments, coupling a detachable component to HMD **1412** causes the detachable component to come into electronic communication with HMD **1412**.

[0155] FIGS. **14A** and **14B** also show that VR system **1400** includes one or more cameras, such as left camera **1439A** and right camera **1439B**, which can be analogous to left and right cameras **1339A** and **1339B** on frame **1304** of eyewear device **1302**. In some embodiments, VR system **1400** includes one or more additional cameras (e.g., cameras **1439C** and **1439D**), which can be configured to augment image data obtained by left and right cameras **1439A** and **1439B** by providing more information. For example, camera **1439C** can be used to supply color information that is not discerned by cameras **1439A** and **1439B**. In some embodiments, one or more of cameras **1439A** to **1439D** can include an optional IR cut filter configured to remove IR light from being received at the respective camera sensors.

[0156] FIG. **15** illustrates a computing system **1520** and an optional housing **1590**, each of which show components that can be included in AR system **1300** and/or VR system **1400**. In some embodiments, more or fewer components can be

included in optional housing **1590** depending on practical restraints of the respective AR system being described.

[0157] In some embodiments, computing system **1520** can include one or more peripherals interfaces **1522A** and/or optional housing **1590** can include one or more peripherals interfaces **1522B**. Each of computing system **1520** and optional housing **1590** can also include one or more power systems **1542A** and **1542B**, one or more controllers **1546** (including one or more haptic controllers **1547**), one or more processors **1548A** and **1548B** (as defined above, including any of the examples provided), and memory **1550A** and **1550B**, which can all be in electronic communication with each other. For example, the one or more processors **1548A** and **1548B** can be configured to execute instructions stored in memory **1550A** and **1550B**, which can cause a controller of one or more of controllers **1546** to cause operations to be performed at one or more peripheral devices connected to peripherals interface **1522A** and/or **1522B**. In some embodiments, each operation described can be powered by electrical power provided by power system **1542A** and/or **1542B**.

[0158] In some embodiments, peripherals interface **1522A** can include one or more devices configured to be part of computing system **1520**, some of which have been defined above and/or described with respect to the wrist-wearable devices shown in FIGS. 11 and 12. For example, peripherals interface **1522A** can include one or more sensors **1523A**. Some example sensors **1523A** include one or more coupling sensors **1524**, one or more acoustic sensors **1525**, one or more imaging sensors **1526**, one or more EMG sensors **1527**, one or more capacitive sensors **1528**, one or more IMU sensors **1529**, and/or any other types of sensors explained above or described with respect to any other embodiments discussed herein.

[0159] In some embodiments, peripherals interfaces **1522A** and **1522B** can include one or more additional peripheral devices, including one or more NFC devices **1530**, one or more GPS devices **1531**, one or more LTE devices **1532**, one or more Wi-Fi and/or Bluetooth devices **1533**, one or more buttons **1534** (e.g., including buttons that are slidable or otherwise adjustable), one or more displays **1535A** and **1535B**, one or more speakers **1536A** and **1536B**, one or more microphones **1537**, one or more cameras **1538A** and **1538B** (e.g., including the left camera **1539A** and/or a right camera **1539B**), one or more haptic devices **1540**, and/or any other types of peripheral devices defined above or described with respect to any other embodiments discussed herein.

[0160] AR systems can include a variety of types of visual feedback mechanisms (e.g., presentation devices). For example, display devices in AR system **1300** and/or VR system **1400** can include one or more liquid-crystal displays (LCDs), light emitting diode (LED) displays, organic LED (OLED) displays, and/or any other suitable types of display screens. Artificial-reality systems can include a single display screen (e.g., configured to be seen by both eyes), and/or can provide separate display screens for each eye, which can allow for additional flexibility for varifocal adjustments and/or for correcting a refractive error associated with a user's vision. Some embodiments of AR systems also include optical subsystems having one or more lenses (e.g., conventional concave or convex lenses, Fresnel lenses, or adjustable liquid lenses) through which a user can view a display screen.

[0161] For example, respective displays **1535A** and **1535B** can be coupled to each of the lenses **1306-1** and **1306-2** of AR system **1300**. Displays **1535A** and **1535B** may be coupled to each of lenses **1306-1** and **1306-2**, which can act together or independently to present an image or series of images to a user. In some embodiments, AR system **1300** includes a single display **1535A** or **1535B** (e.g., a near-eye display) or more than two displays **1535A** and **1535B**. In some embodiments, a first set of one or more displays **1535A** and **1535B** can be used to present an augmented-reality environment, and a second set of one or more display devices **1535A** and **1535B** can be used to present a virtual-reality environment. In some embodiments, one or more waveguides are used in conjunction with presenting artificial-reality content to the user of AR system **1300** (e.g., as a means of delivering light from one or more displays **1535A** and **1535B** to the user's eyes). In some embodiments, one or more waveguides are fully or partially integrated into the eyewear device **1302**. Additionally, or alternatively to display screens, some artificial-reality systems include one or more projection systems. For example, display devices in AR system **1300** and/or VR system **1400** can include micro-LED projectors that project light (e.g., using a waveguide) into display devices, such as clear combiner lenses that allow ambient light to pass through. The display devices can refract the projected light toward a user's pupil and can enable a user to simultaneously view both artificial-reality content and the real world. Artificial-reality systems can also be configured with any other suitable type or form of image projection system. In some embodiments, one or more waveguides are provided additionally or alternatively to the one or more display(s) **1535A** and **1535B**.

[0162] Computing system **1520** and/or optional housing **1590** of AR system **1300** or VR system **1400** can include some or all of the components of a power system **1542A** and **1542B**. Power systems **1542A** and **1542B** can include one or more charger inputs **1543**, one or more PMICs **1544**, and/or one or more batteries **1545A** and **1544B**.

[0163] Memory **1550A** and **1550B** may include instructions and data, some or all of which may be stored as non-transitory computer-readable storage media within the memories **1550A** and **1550B**. For example, memory **1550A** and **1550B** can include one or more operating systems **1551**, one or more applications **1552**, one or more communication interface applications **1553A** and **1553B**, one or more graphics applications **1554A** and **1554B**, one or more AR processing applications **1555A** and **1555B**, and/or any other types of data defined above or described with respect to any other embodiments discussed herein.

[0164] Memory **1550A** and **1550B** also include data **1560A** and **1560B**, which can be used in conjunction with one or more of the applications discussed above. Data **1560A** and **1560B** can include profile data **1561**, sensor data **1562A** and **1562B**, media content data **1563A**, AR application data **1564A** and **1564B**, and/or any other types of data defined above or described with respect to any other embodiments discussed herein.

[0165] In some embodiments, controller **1546** of eyewear device **1302** may process information generated by sensors **1523A** and/or **1523B** on eyewear device **1302** and/or another electronic device within AR system **1300**. For example, controller **1546** can process information from acoustic sensors **1325-1** and **1325-2**. For each detected sound, controller **1546** can perform a direction of arrival (DOA) estimation to

estimate a direction from which the detected sound arrived at eyewear device **1302** of AR system **1300**. As one or more of acoustic sensors **1525** (e.g., the acoustic sensors **1325-1**, **1325-2**) detects sounds, controller **1546** can populate an audio data set with the information (e.g., represented in FIG. **10** as sensor data **1562A** and **1562B**).

[0166] In some embodiments, a physical electronic connector can convey information between eyewear device **1302** and another electronic device and/or between one or more processors **1348**, **1548A**, **1548B** of AR system **1300** or VR system **1400** and controller **1546**. The information can be in the form of optical data, electrical data, wireless data, or any other transmittable data form. Moving the processing of information generated by eyewear device **1302** to an intermediary processing device can reduce weight and heat in the eyewear device, making it more comfortable and safer for a user. In some embodiments, an optional wearable accessory device (e.g., an electronic neckband) is coupled to eyewear device **1302** via one or more connectors. The connectors can be wired or wireless connectors and can include electrical and/or non-electrical (e.g., structural) components. In some embodiments, eyewear device **1302** and the wearable accessory device can operate independently without any wired or wireless connection between them.

[0167] In some situations, pairing external devices, such as an intermediary processing device (e.g., HIPD **706**, **806**, **906**) with eyewear device **1302** (e.g., as part of AR system **1300**) enables eyewear device **1302** to achieve a similar form factor of a pair of glasses while still providing sufficient battery and computation power for expanded capabilities. Some, or all, of the battery power, computational resources, and/or additional features of AR system **1300** can be provided by a paired device or shared between a paired device and eyewear device **1302**, thus reducing the weight, heat profile, and form factor of eyewear device **1302** overall while allowing eyewear device **1302** to retain its desired functionality. For example, the wearable accessory device can allow components that would otherwise be included on eyewear device **1302** to be included in the wearable accessory device and/or intermediary processing device, thereby shifting a weight load from the user's head and neck to one or more other portions of the user's body. In some embodiments, the intermediary processing device has a larger surface area over which to diffuse and disperse heat to the ambient environment. Thus, the intermediary processing device can allow for greater battery and computation capacity than might otherwise have been possible on eyewear device **1302** standing alone. Because weight carried in the wearable accessory device can be less invasive to a user than weight carried in the eyewear device **1302**, a user may tolerate wearing a lighter eyewear device and carrying or wearing the paired device for greater lengths of time than the user would tolerate wearing a heavier eyewear device standing alone, thereby enabling an artificial-reality environment to be incorporated more fully into a user's day-to-day activities.

[0168] AR systems can include various types of computer vision components and subsystems. For example, AR system **1300** and/or VR system **1400** can include one or more optical sensors such as two-dimensional (2D) or three-dimensional (3D) cameras, time-of-flight depth sensors, structured light transmitters and detectors, single-beam or sweeping laser rangefinders, 3D LiDAR sensors, and/or any

other suitable type or form of optical sensor. An AR system can process data from one or more of these sensors to identify a location of a user and/or aspects of the user's real-world physical surroundings, including the locations of real-world objects within the real-world physical surroundings. In some embodiments, the methods described herein are used to map the real world, to provide a user with context about real-world surroundings, and/or to generate digital twins (e.g., interactable virtual objects), among a variety of other functions. For example, FIGS. **14A** and **14B** show VR system **1400** having cameras **1439A** to **1439D**, which can be used to provide depth information for creating a voxel field and a two-dimensional mesh to provide object information to the user to avoid collisions.

[0169] In some embodiments, AR system **1300** and/or VR system **1400** can include haptic (tactile) feedback systems, which may be incorporated into headwear, gloves, body suits, handheld controllers, environmental devices (e.g., chairs or floor mats), and/or any other type of device or system, such as the wearable devices discussed herein. The haptic feedback systems may provide various types of cutaneous feedback, including vibration, force, traction, shear, texture, and/or temperature. The haptic feedback systems may also provide various types of kinesthetic feedback, such as motion and compliance. The haptic feedback may be implemented using motors, piezoelectric actuators, fluidic systems, and/or a variety of other types of feedback mechanisms. The haptic feedback systems may be implemented independently of other artificial-reality devices, within other artificial-reality devices, and/or in conjunction with other artificial-reality devices.

[0170] In some embodiments of an artificial reality system, such as AR system **1300** and/or VR system **1400**, ambient light (e.g., a live feed of the surrounding environment that a user would normally see) can be passed through a display element of a respective head-wearable device presenting aspects of the AR system. In some embodiments, ambient light can be passed through a portion less than all of an AR environment presented within a user's field of view (e.g., a portion of the AR environment co-located with a physical object in the user's real-world environment that is within a designated boundary (e.g., a guardian boundary) configured to be used by the user while they are interacting with the AR environment). For example, a visual user interface element (e.g., a notification user interface element) can be presented at the head-wearable device, and an amount of ambient light (e.g., 15-50% of the ambient light) can be passed through the user interface element such that the user can distinguish at least a portion of the physical environment over which the user interface element is being displayed.

[0171] The process parameters and sequence of the steps described and/or illustrated herein are given by way of example only and can be varied as desired. For example, while the steps illustrated and/or described herein may be shown or discussed in a particular order, these steps do not necessarily need to be performed in the order illustrated or discussed. The various exemplary methods described and/or illustrated herein may also omit one or more of the steps described or illustrated herein or include additional steps in addition to those disclosed.

[0172] The preceding description has been provided to enable others skilled in the art to best utilize various aspects of the exemplary embodiments disclosed herein. This exem-

plary description is not intended to be exhaustive or to be limited to any precise form disclosed. Many modifications and variations are possible without departing from the spirit and scope of the present disclosure. The embodiments disclosed herein should be considered in all respects illustrative and not restrictive. Reference should be made to the appended claims and their equivalents in determining the scope of the present disclosure.

[0173] Unless otherwise noted, the terms “connected to” and “coupled to” (and their derivatives), as used in the specification and claims, are to be construed as permitting both direct and indirect (i.e., via other elements or components) connection. In addition, the terms “a” or “an,” as used in the specification and claims, are to be construed as meaning “at least one of.” Finally, for ease of use, the terms “including” and “having” (and their derivatives), as used in the specification and claims, are interchangeable with and have the same meaning as the word “comprising.”

[0174] It will be understood that when an element such as a layer or a region is referred to as being formed on, deposited on, or disposed “on” or “over” another element, it may be located directly on at least a portion of the other element, or one or more intervening elements may also be present. In contrast, when an element is referred to as being “directly on” or “directly over” another element, it may be located on at least a portion of the other element, with no intervening elements present.

[0175] As used herein, the term “approximately” in reference to a particular numeric value or range of values may, in certain embodiments, mean and include the stated value as well as all values within 10% of the stated value. Thus, by way of example, reference to the numeric value “50” as “approximately 50” may, in certain embodiments, include values equal to 50 ± 5 , i.e., values within the range 45 to 55.

[0176] As used herein, the term “substantially” in reference to a given parameter, property, or condition may mean and include to a degree that one of ordinary skill in the art would understand that the given parameter, property, or condition is met with a small degree of variance, such as within acceptable manufacturing tolerances. By way of example, depending on the particular parameter, property, or condition that is substantially met, the parameter, property, or condition may be at least approximately 90% met, at least approximately 95% met, or even at least approximately 99% met.

[0177] While various features, elements or steps of particular embodiments may be disclosed using the transitional phrase “comprising,” it is to be understood that alternative embodiments, including those that may be described using the transitional phrases “consisting of” or “consisting essentially of,” are implied. Thus, for example, implied alternative embodiments to a lens that comprises or includes polycarbonate include embodiments where a lens consists essentially of polycarbonate and embodiments where a lens consists of polycarbonate.

What is claimed is:

1. A method comprising:
 - forming a layer of reactive mesogen comprising an internal grating patterning; and
 - modifying a cross-sectional shape of the layer of reactive mesogen proximate to the internal grating pattern.
2. The method of claim 1, wherein forming the layer of reactive mesogen comprises spin coating.

3. The method of claim 1, wherein the internal grating pattern comprises locally polymerized liquid crystal molecules.

4. The method of claim 1, wherein modifying the cross-sectional shape of the layer of reactive mesogen comprises plasma etching.

5. The method of claim 1, wherein forming the layer of reactive mesogen comprises:

- forming a first layer of reactive mesogen comprising a first internal grating patterning; and

- forming a second layer of reactive mesogen comprising a second internal grating patterning over the first layer of reactive mesogen.

6. The method of claim 1, wherein modifying the shape of the layer of reactive mesogen comprises:

- forming a layer of photoresist over the layer of reactive mesogen;

- positioning a grayscale photomask over the layer of photoresist, the photomask having transparent areas corresponding to a gray-tone pattern;

- directing exposing light through the photomask and onto the layer of photoresist;

- developing the photoresist to produce a three dimensional structure in the layer of photoresist; and

- plasma etching the layer of photoresist and the layer of reactive mesogen to form the three dimensional structure in the layer of reactive mesogen.

7. The method of claim 6, wherein the three dimensional structure in the layer of reactive mesogen comprises sloped sidewalls.

8. The method of claim 6, wherein the three dimensional structure in the layer of reactive mesogen comprises sidewalls having a profile selected from the group consisting of convex, concave, and spline.

9. The method of claim 6, wherein the three dimensional structure in the layer of reactive mesogen comprises a variable thickness.

10. An optical grating comprising:

- a layer comprising a liquid crystal polymer, the layer including an internal grating pattern defined by locally polymerized liquid crystal molecules, wherein a cross-sectional shape of the layer varies across the internal grating pattern.

11. The optical grating of claim 10, wherein the cross-sectional shape comprises a variable thickness.

12. The optical grating of claim 10, wherein the cross-sectional shape comprises sidewalls having a profile selected from the group consisting of convex, concave, and spline.

13. A method comprising:

- forming a layer of photo-alignment material over a substrate;

- selectively irradiating the layer of photo-alignment material with polarized light to form a grating pattern in the layer of photo-alignment material;

- forming a layer of reactive mesogen over the patterned layer of photo-alignment material;

- transferring the grating patterning into the layer of reactive mesogen;

- forming a layer of photoresist over the layer of reactive mesogen;

- directing exposing light through a grayscale photomask having transparent areas corresponding to a gray-tone pattern to produce masked light;

- directing the masked light onto the layer of photoresist;

developing the photoresist to produce a three dimensional structure in the layer of photoresist; and
plasma etching the layer of photoresist and the layer of reactive mesogen to form the three dimensional structure in the layer of reactive mesogen.

14. The method of claim **13**, wherein the layer of reactive mesogen is formed by spin coating and comprises a substantially constant thickness prior to the plasma etching.

15. The method of claim **13**, wherein the layer of reactive mesogen is formed by printing and comprises a variable thickness prior to the plasma etching.

16. The method of claim **13**, wherein forming the layer of reactive mesogen comprises:

forming a first layer of reactive mesogen over the patterned layer of photo-alignment material; and
forming a second layer of reactive mesogen over the first layer of reactive mesogen.

17. The method of claim **13**, wherein transferring the grating patterning into the layer of reactive mesogen comprises self-alignment of liquid crystals within the layer of reactive mesogen.

18. The method of claim **13**, wherein the three dimensional structure in the layer of reactive mesogen comprises sloped sidewalls.

19. The method of claim **13**, wherein the three dimensional structure in the layer of reactive mesogen comprises sidewalls having a profile selected from the group consisting of convex, concave, and spline.

20. The method of claim **13**, wherein the three dimensional structure in the layer of reactive mesogen comprises a variable thickness.

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